ELEMENITAL ABUNDANCES IN NGC 3516

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ABSTRACT

We present Reflection Grating Spectrometer data from an XMM-Newton observation of the Seyfert 1 galaxy NGC 3516, taken while the continuum source was in an extremely low flux state. This observation offers a rare opportunity for a detailed study of emission from a Seyfert 1 galaxy, as these are usually dominated by high nuclear continuum levels and heavy absorption. The spectrum shows numerous narrow emission lines (FWHM < 1300 km s$^{-1}$) in the 0.3–2 keV range, including the H-like lines of C, N, and O and the He-like lines of N, O, and Ne. The emission-line ratios and the narrow width of the radiative recombination continuum of C$^+$ indicate that the gas is photoionized and of fairly low temperature ($kT < 0.01$ keV). The availability of emission lines from different elements for two isoelectronic sequences allows us to constrain the element abundances. These data show that the N lines are far stronger than would be expected from gas of solar abundances. Based on our photoionization models, we find that nitrogen is overabundant in the central regions of the galaxy, compared to carbon, oxygen, and neon, by at least a factor of 2.5. We suggest that this is the result of secondary production of nitrogen in intermediate-mass stars and indicative of the history of star formation in NGC 3516.

Subject headings: galaxies: abundances — galaxies: active — galaxies: individual (NGC 3516) — galaxies: nuclei — galaxies: Seyfert

1. INTRODUCTION

X-ray and UV spectra of the Seyfert 1 galaxy NGC 3516 ($z = 0.008836 \pm 0.000023$; Keel 1996) have shown evidence for a significant column of ionized gas along the line of sight to the nucleus (Kripp et al. 1996; Mathur, Wilkes, & Aldcroft 1997; Costantino et al. 2000; Netzer et al. 2002; Kraemer et al. 2002). A recent Chandra observation of this source found it to exist at a historical low state. The spectrum at that epoch and comparison with previous X-ray data led Netzer et al. (2002) to suggest a model for NGC 3516 in which a constant column of gas reacts to changes in the nuclear ionizing flux. That gas was constrained to have density greater than $2.4 \times 10^{6}$ cm$^{-3}$ and exist at a distance less than $6 \times 10^{17}$ $L_H^2$ cm from the nucleus. Netzer et al. (2002) also detected a strong O vii line at 0.561 keV and marginally detected an N vii line at 0.419 keV line. Differences in the Chandra Low Energy Transmission Grating (LETG) data appeared consistent with emission from the X-ray absorber.

We present here XMM-Newton (hereafter XMM) Reflection Grating Spectrometer (RGS) grating spectra of NGC 3516. These data allow us to rethink the origin of the X-ray line emission in NGC 3516.

2. THE XMM RGS OBSERVATION

An XMM observation of the Seyfert 1 galaxy NGC 3516 was performed covering 2001 November 9 UT 23:12:51–November 11 UT 10:54:19. This observation was part of a multisatellite campaign including overlapping observations by RXTE and Chandra. The Fe Kα line shows interesting structure and evolution during the observation, and the combined data in the hard X-ray regime are detailed by Turner et al. (2002). Here we present a detailed analysis of the XMM RGS grating data from 2001 November.

As noted by Turner et al. (2002), NGC 3516 had a flux $F_{2-10keV} \approx (1.3-1.5) \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$, during the 2001 November observations. The source was in this flux state during the previous Chandra LETG observation (Netzer et al. 2002) and as observed by ASCA during 1999 (Fig. 1). Unfortunately, no useful RGS data were obtained from an earlier epoch observation with XMM in 2001 April, because of background flares during a period of high solar activity.

RGS data were processed using the SAS 5.3.3 version of RGSPROC, and spectra were extracted using standard regions. The source cell encompassing 97% of the cross-dispersed counts) and extraction criteria, resulting in exposure times of ~114 ks in RGS-1 (R1) and ~108 ks in RGS-2 (R2). The full-band (0.34–2.0 keV) RGS background-subtracted count rates were $0.062 \pm 0.0008$ (R1) and $0.067 \pm 0.0008$ (R2). The background comprised 17% of the total count rate in R1 and R2. We note that because of problems with some of the CCD chips onto which the RGS spectrum is dispersed, there are two prominent data gaps evident; R1 has a gap between ~0.9 and 1.2 keV and R2 has a gap between ~0.51 and 0.62 keV. We note that in this analysis we adopted $cz = 2649$ km s$^{-1}$ (Keel 1996).

Ignoring emission and absorption lines for the moment, we find a good parameterization of the continuum shape in RGS data over the 0.3–2 keV band using a power law of photon index $\Gamma = 2.17 \pm 0.04$ attenuated by a Galactic column of cold gas $N_H = 2.9 \times 10^{20}$ cm$^{-2}$ plus a column of ionized gas with $N_{H_{UV}} = 7.7 \times 10^{21}$ cm$^{-2}$. Such a column of ionized gas is expected from the UV and LETG analyses (Netzer et al. 2002; Kraemer et al. 2002) of data from an epoch close in time to these RGS data (and the ionized gas is modeled using CLOUDY, ver. 90, for solar-abundance material; Ferland et al. 1998).
improves the fit from $\chi^2 = 1594$ for 639 degrees of freedom (dof) to 1180 for 638 dof and provides a good model to the gross shape of the soft spectrum. Figure 2 shows the data compared with this model. However, our parameterization of the continuum shape is not the only possible model. A recent alternative applied to some Seyfert spectra parameterizes broad spectral wiggles as emission lines due to ionized material in the accretion disk (see, e.g., Branduardi-Raymont et al. 2001). However, we do not pursue such a parameterization in this paper. The absorption edges expected from the (previously observed) ionized absorber provide a good description of most of the broad features, and we believe that this makes our interpretation of the spectrum a compelling way to proceed for this observation of NGC 3516.

The most immediate result evident from Figure 2 is that the RGS spectra show several prominent emission lines. The two strongest lines are those at 0.4198 and 0.5614 keV. We identify these with forbidden components of N vi and O vii, respectively. These two strong lines were measured carefully to determine bulk and turbulent velocities of the emitting gas. For the N vi line we measured a rest energy.
$E = 419.8 \pm 0.2$ eV and for the O\textsc{vii} line $E = 561.4 \pm 0.3$ eV. Errors are at 90\% confidence. Intrinsic line widths were found to be $\sigma = 3.8^{+1.5}_{-1.3} \times 10^{-4}$ and $5.6^{+1.4}_{-1.6} \times 10^{-4}$ keV, respectively. The energy for O\textsc{vii} corresponds to blueshift of 214$^{+160}_{-40}$ km s$^{-1}$, while for N\textsc{vi} the blueshift is 143$^{+143}_{-80}$ km s$^{-1}$, i.e., consistent with no blueshift. For comparison, the absolute wavelength calibration for the RGS is $\approx 8$ mA, or $\approx 100$ km s$^{-1}$ at 0.5610 keV. Thus, the evidence for a blueshift for the O\textsc{vii} line is marginal; the lower limit is close to the accuracy of the detector absolute wavelength calibration.

The line widths correspond to velocities FWHM(N\textsc{vi}) = 646$^{+381}_{-646}$ km s$^{-1}$ and FWHM(O\textsc{vii}) = 704$^{+554}_{-704}$ km s$^{-1}$. Line widths are consistent with zero; the upper limits constrain velocity broadening to $\lesssim 1300$ km s$^{-1}$. (For comparison, the FWHM resolution of R1 is $\approx 680$ km s$^{-1}$ at the observed energy of N\textsc{vi}, 0.416 keV, and $\approx 850$ km s$^{-1}$ at the observed energy of O\textsc{vii}, 0.556 keV.) Changes in the detector effective area with energy cause some apparent asymmetries at first glance, as the effective area changes significantly across some line profiles (e.g., O\textsc{vii} at 0.654 keV). However, we find no true asymmetry in any emission-line profile.

To search for weak emission lines, we slid a Gaussian template across the data, testing for an improvement to the fit at every resolution element compared to our model of the underlying continuum. The data were first binned by a factor of 8 to a bin size of 0.32 Å, to ensure that there were more than 20 photons in each spectral bin so $\chi^2$ fitting could be employed. Examination of the RGS background spectra shows a broad bump centered around 0.39 keV (not fully understood, but thought likely because of relatively high dark current in CCD2 for both RGS instruments; XMM Users’ Handbook; also see den Herder et al. 2001). Other known features in the RGS background include emission from Al K\textalpha{} close to 1.5 keV due to Al in the detector housing. This means that we need to subtract the RGS background to ensure that we isolate the spectral properties of the source. Figure 3 shows the results of this sliding Gaussian test against the observed data in red. Plotted is the improvement in the fit statistic. This plot is useful in assessing the significance of each line, but not the strength of the line. It can be seen that the addition of an emission feature results in a large improvement in $\chi^2$ statistic at several energies.

In order to assess the reality of these features, we have constructed a series of simulated data sets. For each RGS, 20 separate background spectra were generated by randomly adding the appropriate Poisson noise to each channel in the observed background spectrum. Similarly, 20 simulated source spectra were generated for each RGS, again with Poisson noise introduced, using our model of the underlying continuum convolved with the instrumental response. These simulated data sets were then combined and 20 R1+R2 pairs analyzed in the same manner as the observed spectra above. Specifically, the sliding Gaussian template against the data, testing for an improvement to the fit at every resolution element compared to our model of the underlying continuum. The data were first binned by a factor of 8 to a bin size of 0.32 Å, to ensure that there were more than 20 photons in each spectral bin so $\chi^2$ fitting could be employed. Examination of the RGS background spectra shows a broad bump centered around 0.39 keV (not fully understood, but thought likely because of relatively high dark current in CCD2 for both RGS instruments; XMM Users’ Handbook; also see den Herder et al. 2001). Other known features in the RGS background include emission from Al K\textalpha{} close to 1.5 keV due to Al in the detector housing. This means that we need to subtract the RGS background to ensure that we isolate the spectral properties of the source. Figure 3 shows the results of this sliding Gaussian test against the observed data in red. Plotted is the improvement in the fit statistic. This plot is useful in assessing the significance of each line, but not the strength of the line. It can be seen that the addition of an emission feature results in a large improvement in $\chi^2$ statistic at several energies.

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test was performed for each of the 20 pairs, and the maximum reduction in fit statistic at each energy noted. The result is plotted in blue in Figure 3 and therefore represents a 95% significance threshold at each energy (and takes into account all instrumental and background features).

Including the N \text{vi} and O \text{vii} lines discussed above, we find a total of 13 emission features (some of which are blends) in the observed spectrum above the 95% confidence threshold. Ten of these 13 occur at energies consistent with atomic transitions of abundant ions and have understandable intensity ratios (below). Thus, we consider these 10 features to be robust detections. They are labeled on Figure 3 and listed in Table 1. Of the remaining three features, that at 0.39 keV is most likely due to the detector background.

![Figure 3](image)

**TABLE 1**

| Energy\(^a\) (keV) | Line ID | Predicted Rest Energy (keV) | Flux 1\(^c\) \(\times 10^{-5}\) photons cm\(^{-2}\) s\(^{-1}\) | Flux 2 \(\times 10^{-14}\) ergs cm\(^{-2}\) s\(^{-1}\) |
|------------------|---------|-----------------------------|-----------------------------|-----------------------------|
| 0.3671           | C \text{vi} Ly\(\alpha\) | 0.366                        | 46 ± 15                      | 1.58                        |
| 0.4198           | N \text{vi}f                      | 0.4198                       | 119 ± 17                     | 3.18                        |
| 0.4280           | N \text{vi}i+r                  | 0.4263/0.4307               | 41 ± 13                      | 1.69                        |
| 0.4913           | C \text{vi} RRC                | 0.4900                      | 29\(^{+10}_{-11}\)           | 3.35                        |
| 0.5004           | N \text{vii}                  | 0.5002                     | 37 ± 14                      | 1.06                        |
| 0.5614           | O \text{vii}f\(^d\)            | 0.5610                     | 122 ± 17                     | 4.21                        |
| 0.5681           | O \text{vii}i\(^d\)            | 0.5686                     | 30 ± 12                      | 1.20                        |
| 0.5727           | O \text{vii}r\(^d\)            | 0.5739                     | 49 ± 12                      | 1.38                        |
| 0.6540           | O \text{viii}                  | 0.6510                     | 48 ± 12                      | 0.82                        |
| 0.9047           | Ne \text{ix}f\(^e\)            | 0.9055                     | 25\(^{+10}_{-9}\)            | 0.57                        |

\(\text{a}\) The measured rest energy of the line, corrected for the systematic velocity of the host galaxy.

\(\text{b}\) Counts attributed to the line (after subtraction of the continuum flux). Errors are \(1\sigma\).

\(\text{c}\) Lines assumed to have widths FWHM = 650 km s\(^{-1}\).

\(\text{d}\) RGS 1 only.

\(\text{e}\) RGS 2 only.
described above. The final two features (at 0.697 and 0.706 keV and apparent strengths corresponding to $\sim 0.4 \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$) do occur at energies close to atomic transitions. The former is consistent with the O vii ($1s^2 \rightarrow 1s4p$) resonance line at 0.698 keV. However, the lack of any indication of the O vii ($1s^2 \rightarrow 1s3p$) line at 0.665 keV makes such an interpretation extremely unlikely. The line at 0.706 keV could be identified with S xiv radiative recombination continuum (RRC) at 0.707 keV. However, such an interpretation would lead us to expect a much stronger O vii RRC at 0.871 keV than observed. In summary, only the 10 emission lines that we believe secure ($\Delta \chi^2 > 10$) and attributable to NGC 3516 appear in Table 1.

While some of the detected features have some significant width, e.g., the C v RRC, the features were too weak for us to fit for the width and thus the temperature of the emitting gas. However, we did obtain an upper limit on width, $kT \lesssim 0.01$ keV, i.e., $T \lesssim 120,000$ K. This is consistent with the width of the RRC features in NGC 1068, based on which Kinkhabwala et al. (2002) argued that the X-ray-emitting plasma was purely photoionized.

The emission lines were assumed to originate outside of the UV absorber (i.e., not absorbed by it). If the emitter were inside the UV absorber it would have to reside within $10^{16}$ cm of the nucleus, with a density $10^9$ cm$^{-3}$ or so (Kraemer et al. 2002). While such a location is possible, the velocity widths of the emission lines at FWHM $< 1300$ km s$^{-1}$ are rather narrow for such a small radial location. These widths are more suggestive of an origin on the parsec scale. Furthermore, some results from Seyfert 2 galaxies suggest that the X-ray-emitting gas in general has extent on the 10–100 pc size scale (see, e.g., Sako et al. 2000). All things considered, it seems most likely that the emitting gas lies outside of the UV absorber in this case. The fact that the absorption edges are imprinted on the soft spectrum must then be explained as the soft band having a significant contribution from nuclear continuum emission, transmitted through the UV absorber (the fraction of the nuclear continuum scattered by the line-emitting gas is negligible, as shown in § 4.2). Thus, we suggest a full model of an absorbed continuum component plus unabsorbed lines (with the Galactic column absorbing all). The line fluxes in Table 1 are the inferred intrinsic fluxes at the source (i.e., corrected for Galactic absorption). In addition to tabulating the fitted line fluxes, we noted the total counts in the bin, those attributable to the continuum emission, and thus those attributable to the emission line itself. Errors are calculated on the counts in the line, and the same fractional errors are applicable to the fluxes listed.

The process was repeated to search for weak absorption lines. Following a process similar to that used to detect the emission lines, we found evidence for an absorption feature at 0.358 keV and broad features centered on 0.753 and 0.96 keV. The former has no obvious identification. The feature at 0.75 keV, while close to a jump in detector efficiency, appears real, and we identify this with the unresolved transition array due to inner-shell absorption by Fe x–xi M-shell ions, as observed in some other AGNs (e.g., IRAS 13349+2438; Sako et al. 2001). The feature at $\sim 0.96$ keV may be a blend of Fe lines from highly ionized gas (Fe xx–xxiv). Much weaker features at 0.54 and 0.61 keV do not have clear identifications.

Absorption lines and edges were expected to be detected in NGC 3516 from transmission of the nuclear continuum through ionized gas, previously observed in this source (see, e.g., Kriss et al. 1996; Netzer et al. 2002; Kraemer et al. 2002). The overall shape of the RGS spectra shows the imprint of the absorption edges expected from the X-ray absorption associated with the gas measured by STIS (Kraemer et al. 2002). The width of the UV absorption lines is $\sim 20–70$ km s$^{-1}$; X-ray absorption lines with the same velocity structure would be too narrow to detect with the RGS (or Chandra grating data).

3. FUSE DATA

We reduced data from an archival Far Ultraviolet Spectroscopic Explorer (FUSE) spectrum, originally obtained on 2000 April 17, again, while NGC 3516 was in an extremely low flux state (see Kraemer et al. 2002). From the FUSE spectrum we measured an O vii $\lambda 1038$ flux of $\approx 1.6 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$, with an FWHM of $\sim 250$ km s$^{-1}$. Given the intrinsic 2:1 emission ratio of O vii $\lambda 1032$/O vii $\lambda 1038$ line fluxes, the total O vi flux should be $\approx 4.0 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$. However, as noted by Hutchings et al. (2001) in their analysis of this spectrum, the observed O vi doublet ratio is $\sim 1:1$, which they attributed to line transfer effects in optically thin gas. We think that it is more likely that the lines are absorbed by intervening gas, which may explain the asymmetric line profiles (see Hutchings et al. 2001) and the narrowness of the O vi lines compared to the X-ray lines. However, it is not necessary that this absorption arise in the same material that produces the deep, variable X-ray absorption discussed in Netzer et al. (2002) and Kraemer et al. (2002) but could be a relatively small column of ionized gas (e.g., $\sim 10^{20}$ cm$^{-2}$, $U \sim 0.5$) that covers the NLR of NGC 3516. This component may only be detectable when viewed against the NLR emission, much of which was missed in the small, 0$''$2 by 0$''$2, STIS aperture, but is well covered by the 20$''$0 by 20$''$0 FUSE aperture. (At a distance of 35.7 Mpc for NGC 3516, 1$''$ = 173 pc.) In fact, similar evidence for absorbed UV narrow-line profiles has been seen in STIS spectra of NGC 1068 (Kraemer & Crenshaw 2000).
species; the resonance line \((1s^2 \cdot 1s^1p \cdot 1s^2p \cdot 1P_1)\), the two
intercombination lines \((1s^2 \cdot 1s^1p \cdot 1s^2p \cdot 2P_{2,1})\), and the forbidden
line \((1s^2 \cdot 1s^1p \cdot 1s^2s \cdot 3S_1)\). The ratios of the forbidden line to the
two intercombination lines (the \(R\) ratio) is sensitive to den-
sity, while the ratio of the sum of the forbidden and inter-
combination lines to the resonance line (the \(G\) ratio) is
sensitive to electron temperature. If the resonance lines are
relatively strong, the latter ratio can indicate temperatures
in excess of those expected for a photoionized plasma. How-
ever, the resonance lines can be also be photoexcited (Sako
et al. 2000); hence, the \(G\) ratio may not be a reliable indica-
tor of either the temperature or the means of excitation of
the plasma. Based on their analysis of an XMM-Newton
RGS spectrum of NGC 1068, Kinkhabwala et al. (2002)
suggested that the excess emission in virtually all the
detected resonance lines was the result of photoexcitation in
a purely photoionized plasma.

In these data, the \(R\) ratio of the \(O\ vii\) line to the \(f\) lines is
\(\sim 3.5\) (see Table 1), which for a photoionized plasma implies
an electron density \(n_e\) \(\sim\) several times \(10^8\) cm\(^{-3}\) (Porquet &
Dubau 2000). However, the weakness of the intercombi-
nation lines, plus any underlying contribution from the wings
of the adjacent forbidden and resonance lines, can easily
lead to an overestimate of the flux. Hence, it is likely that
\(n_e\) is lower. Furthermore, at sufficiently high density, the meta-
stable \(1s^2 \cdot 1S_1\) level begins to collisionally depopulate, sup-
pressing the forbidden line of the He-like triplet. For \(N\ vii\)
this occurs at \(n_e > 10^6\) cm\(^{-3}\), while the depopulation of cor-
responding \(O\ vii\) level occurs at densities a factor of \(\sim 10\) greater
(Porquet & Dubau 2000). Given the relative strengths of the \(N\ vii\) and \(O\ vii\) forbidden lines, we suggest that the
average density in the emission-line gas is \(n_e \lesssim 10^8\)
\(\text{cm}^{-3}\).

4.2. Photoionization Models

Photoionization models of the X-ray emission-line gas
were generated using the Beta 5 version of CLOUDY
(G. Ferland 2003, private communication). This version of
the code includes new atomic data for the He-like ions. We
modeled the emission-line gas as a single-zoned slab of
atomic gas, irradiated by the central source, for which we
used the same spectral energy distribution and luminosity
\((\sim 10^{33}\text{ ergs s}^{-1})\) described in Kraemer et al. (2002).
As usual, the models are parameterized in terms of the ionization
parameter \(U\), which is the ratio of ionizing photons per H
atom at the ionized face of the slab. We initially assumed
depolar elemental abundances (Grevesse & Anders 1989),
which are, by number relative to H, as follows: He = 0.1,
C = \(3.4 \times 10^{-5}\), N = \(1.2 \times 10^{-4}\), O = \(6.8 \times 10^{-4}\), Ne =
\(1.1 \times 10^{-4}\), Mg = \(3.3 \times 10^{-5}\), Si = \(3.1 \times 10^{-5}\), S = \(1.5 \times
10^{-5}\), and Fe = \(4.0 \times 10^{-5}\). The gas was assumed to be free
of dust.

Prior to generating new models, we explored the possibility
that the X-ray emission lines arise in the UV/X-ray
absorber described in Kraemer et al. (2002). In the current
low-flux state of NGC 3516, the models of the strongest UV
components predicted ratios of ionic columns for \(O\ vii\):
\(O\ vii:O\ vi\) to be roughly \(1.00:0.67:0.03\). Consequently,
little \(O\ vii\) Ly\(\alpha\) emission is expected relative to \(O\ vi\) emis-

\text{ion for the UV gas seen in emission. This is not the case; we
observe enough \(O\ vi\) emission to know there must be an
additional component of higher ionization gas present. We
also note that the model for the production of \(O\ vi\ \lambda 1032,
1038 \text{ emission lines from the UV gas yields fluxes ~20 times
as strong as that of the \(O\ vi\ f\) line. In the data they appear
weaker than this, as noted further below.}

Since the X-ray emission lines cannot be formed in the
UV/X-ray absorbers, we permitted \(U\) and the total column
density \((N_{\text{H}} = \text{H} + \text{H})\) to vary, as a new model
is required for the X-ray–emitting gas. In Table 2, we compare
the model predictions to the measured emission-line fluxes
by scaling the predicted \(O\ vi\ f\) line flux to that observed. We
find that line ratios can be roughly matched using a single-
zoned model, with \(U = 1.1\), \(N_{\text{H}} = 1.5 \times 10^{21}\) \(\text{cm}^{-2}\),
and solar abundances (model 1). In order to boost the strength
of the resonance lines via photoexcitation, we introduced a
turbulent velocity of 50 km s\(^{-1}\), which is roughly equal to
the average FHWM of the individual UV absorbers
(Kraemer et al. 2002). If we assume \(n_e = 10^8\) \(\text{cm}^{-3}\),
our model results place the emission-line gas at a radial distance
of 0.02 pc, although this is within the range determined for
the UV absorbers, since the lower limit to the density is not
well constrained. It is quite plausible that the emission-line
gas lies farther from the nucleus, as we discussed in \(\S\) 2. The
model predicts a mean electron temperature of 7.4 \(\times 10^4\) K,
in agreement with the constraints determined from the \(C\ vii\)
RRC.

The model predictions assuming solar abundance are
within the measurement errors for the \(O\ vii\) He-like lines,
\(Ne\ vi\ f\), and \(O\ vi\ Ly\(\alpha\), while the prediction for \(C\ vi\ Ly\(\alpha\) is
slightly high. However, the strengths of the \(N\ vii\) He-like
lines and \(N\ vii\ Ly\(\alpha\) line are underpredicted by factors of \(\sim 4\)
and \(\sim 2\), respectively, which is strong evidence against
our initial assumption of solar abundances. The apparently
anomalous line ratios in NGC 3516 suggest one of two pos-
sibilities: the other elements, such as C and O, are depleted
onto dust grains (see, e.g., Shields & Kennicutt 1995), or the
N abundance exceeds the solar value.

Consider the case of depletion onto dust grains. UV data
show many cases of enhanced nitrogen relative to carbon,
e.g., NGC 5548 (Crenshaw et al. 2003) and Akn 564
(Crenshaw et al. 2001). In those cases C may be depleted
onto dust grains (see, e.g., Shields & Kennicutt 1995), or the
N abundance exceeds the solar value.

\text{TABLE 2}

| Line         | Model 1a | Model 2b | Model 3c | Measured |
|--------------|----------|----------|----------|----------|
| \(C\ vii\ Ly\(\alpha\) | 1.55     | 1.57     | 0.87     | 1.06 ± 0.35 |
| \(N\ vii\ f\) | 0.57     | 1.43     | 1.44     | 2.13 ± 0.30 |
| \(N\ vii+/f\) | 0.48     | 0.86     | 0.86     | 1.16 ± 0.37 |
| \(N\ vi\)   | 0.53     | 1.10     | 1.19     | 0.85 ± 0.32 |
| \(O\ vii\ f\) | 3.78     | 3.78     | 3.78     | 3.78 ± 0.33 |
| \(O\ vii+/f\) | 0.94     | 0.94     | 0.94     | 1.09 ± 0.44 |
| \(O\ vi\)  | 1.03     | 1.03     | 1.04     | 1.27 ± 0.31 |
| \(O\ vi\ f\) | 1.30     | 1.27     | 1.30     | 1.31 ± 0.33 |
| \(Ne\ vii\ f\) | 0.89     | 0.90     | 0.89     | 0.83 ± 0.33 |

\text{Note.—Fluxes are in units of \(10^{14}\) ergs cm\(^{-2}\) s\(^{-1}\).}

\text{a Solar abundances. Fluxes scaled to the K in f line.}
\text{b N/H \(\sim 2.5\) times solar. Fluxes scaled to the O vi f line.}
\text{c N/H \(\sim 2.5\) times solar; C depleted to 47\% relative to solar. Fluxes
scaled to the O vi f line.}
and Ne cannot be depleted onto dust grains. Thus we rule out depletion.

Hence, it is most likely that nitrogen is overabundant, perhaps by a factor of 2–3. Interestingly, Kinkhabwala et al. (2002) came to a similar conclusion for NGC 1068. As a result, we regenerated the model using an N/H ratio of 2.5 times solar (model 2). As shown in Table 2, the fit for the N v line is quite good. While the N vi lines are much closer to the observed strengths, they are still somewhat underpredicted. The latter may simply be a reflection of the difficulty in matching the emission lines with a single-zoned model, since some additional N vi could arise in a component of lower ionization gas. Our discovery of nitrogen overabundance led us to revisit the absorber used, which fits the UV data and models the broad features in the soft X-ray band. Before doing so, we note that the STIS data on which that absorber was based (Kraemer et al. 2002) showed saturated N and C lines, so limits from those lines did not provide tight constraints on the state of the gas for the UV model. Fine-tuning abundances for the absorber model does not make any significant difference to the fit to broad features and thus to the emission-line analysis and conclusions drawn here.

Based on the model predictions, we can constrain the global covering factor of the emission-line gas. Our predicted flux for O vi f emitted from the illuminated face of the photoionized slab is \(1.7 \times 10^{15} \text{ ergs cm}^{-2} \text{s}^{-1}\). Adopting a distance of 35.7 Mpc for NGC 3516, assuming \(H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}\) (Ferruit, Wilson, & Mulchaey 1998), the total O vi f emission from NGC 3516 is \(5.5 \times 10^{35} \text{ ergs s}^{-1}\). Hence, the emitting surface area must be \(3.2 \times 10^{34} \text{ cm}^2\). Based on our assumed density, \(n_e = 10^4 \text{ cm}^{-3}\), and luminosity in ionizing photons, the emission-line gas lies at a radial distance of \(6.9 \times 10^{16} \text{ cm}\), which yields a total surface area of \(6.0 \times 10^{34} \text{ cm}^2\). Hence, the covering factor of the emission-line gas is \(f_c \approx 0.5\). While we expect that the emission-line gas extends over a range in radial distance, and hence density, the total covering factor will be similar.

From the predicted covering factor and column density, we can determine the fraction of the nuclear continuum reflected via electron scattering within the emission-line gas. Assuming isotropic scattering, at small electron-scattering optical depths \(\tau_e \ll 1\), the reflected fraction of continuum radiation \(f_r \approx N_{\text{electron}}/\sigma_T\), where \(N_{\text{electron}}\) is the electron column density \(\approx N_H\) and \(\sigma_T\) is the Thomson cross section. We find \(f_r \approx 5 \times 10^{-4}\); hence, a negligible fraction of continuum radiation will be scattered into our line of sight by this component.

Returning to the question of the strength of O vi emission, we note that the total O vi flux derived from the FUSE data is \(-4.0 \times 10^{-14} \text{ ergs cm}^{-2} \text{s}^{-1}\). Our X-ray emission-line model predicts a total O vi flux of \(6.75 \times 10^{-14} \text{ ergs cm}^{-2} \text{s}^{-1}\), which, since it is somewhat higher than the FUSE value, may support the indication (from the doublet ratio) that these lines are absorbed. Under the assumption that the strengths of the emission lines are constant, this O vi measurement provides a tight constraint on the ionization state of the NLR gas in which the UV and optical emission-lines arise.

5. DISCUSSION

The relation between abundance and AGN redshift, luminosity, and the interrelation between the AGN and starburst regions are key to understanding AGN formation and evolution. Based on the ratios of the N v \(\lambda 1240\) emission line to C iv \(\lambda 1550\) and He ii \(\lambda 1640\), it has been argued that QSOs show high metallicity (\(Z \geq 1\), where \(Z = 1\) for solar abundances) and, in particular, high N abundance at redshifts as high as \(z \geq 3\), indicative of enrichment due to rapid star formation at epochs as early as \(z \lesssim 1\) Gyr (Hamann & Ferland 1993). Among relatively nearby (\(z \lesssim 0.05\)) AGNs, narrow-line Seyfert 1 galaxies show evidence of large N abundances (see, e.g., Wills et al. 1999). It is, therefore, interesting that the X-ray spectra of NGC 3516, a low-redshift, broad-line Seyfert 1 galaxy, also show evidence for an overabundance by a factor of 2–3 of nitrogen in the central regions of the galaxy, with respect to other heavy elements. Furthermore, Kinkhabwala et al. (2002) presented evidence for a similar enhancement of nitrogen in the prototypical Seyfert 2 galaxy NGC 1068. Also, based on the strength of the N v \(\lambda 1240\) line, there is evidence of anomalous N abundances in the NLRs of the Seyfert 1 galaxies NGC 5548 (Kraemer et al. 1998) and NGC 4151 (Kraemer et al. 2000), although this could be at least partly due to enhanced emission by photoexcitation.

Nitrogen can be synthesized from carbon and oxygen produced within a star, referred to as primary production, or via the CNO process in intermediate-mass stars (\(M \lesssim 7 M_\odot\); see Maeder & Meynet 1989) that already possess C and O, i.e., secondary production (see, e.g., Tinsley 1980). At certain temperatures N is enhanced at the expense of C (while at higher temperatures it would be at the expense of O). Thus, it is possible to observe solar O, Ne, etc., yet obtain enhanced N with subsolar C. The enrichment of nitrogen via secondary production increases with overall metallicity, such that \(N/H \propto (O/H)^2 \propto Z^2\). Since the evidence for overabundant nitrogen is typically the high ratios of N lines to those of C or other heavy elements, one might expect that a factor of 3 enhancement of N/O would require Z \(\sim 3\) and N/H \(\sim 9\) times solar! However, for Z \(\sim 1\), it is still possible to have N/H a few times solar, assuming that the enhancement of nitrogen is accompanied by a loss of carbon and, possibly, oxygen (see, e.g., Maeder & Meynet 1989).

For example, assuming roughly solar initial abundances (Grevesse & Anders 1989), N/H could be 2.5 times solar if approximately half of the carbon were used up in the production of nitrogen. Interestingly, our models with solar carbon abundance overpredicted the strength of the C vi Ly\(\alpha\) line by a factor of \(\sim 1.5\). To explore the possibility that some of the carbon was lost in the production of nitrogen, we generated a third model, with the carbon abundance set to 47% solar (to fully account for the enhancement of nitrogen) and all other model parameters kept identical to those of model 2. The predicted line fluxes for model 3, scaled to the O vi f line, are listed in Table 2. The C vi Ly\(\alpha\) line is now within the measurement errors, while the predictions for the other lines are essentially unchanged from those of model 2. Hence, the emission-line fluxes are consistent with emission from photoionized gas, in which the nitrogen is enhanced and the carbon depleted by the same amount. If the anomalous N/O and N/H ratios are consistent with Z \(\sim 1\) and are the result of nitrogen production in intermediate-mass stars, these results provide tight constraints on the history of star formation in the nucleus of NGC 3516.
6. CONCLUSIONS

We have used XMM-Newton RGS gratings spectral data to examine the physical conditions within the X-ray emission-line gas in the Seyfert 1 galaxy NGC 3516. The spectra show emission lines from the He-like ions of N, O, and Ne and H-like ions of C, N, and O. Also, we have detected RRCs from C vi and O vii. We have shown the following:

1. The RGS data show the soft X-ray absorber to be consistent with the UV absorbers detected in earlier HST STIS observations. However, the UV absorbers cannot account for the X-ray line emission. Although the UV absorbers could account for some of the N vi and O vii emission, they are generally in too low an ionization state to produce any of the higher ionization lines detected in the RGS spectra. Furthermore, if the emission from the UV absorbers were scaled to fit the O vii/f component, the models predict O vii \( \lambda \lambda 1032, 1038 \) lines almost an order of magnitude stronger than observed in a recent FUSE spectrum. While some line variability may occur, an order-of-magnitude change in O vi between the FUSE observation and the epoch reported here is highly unlikely.

2. From the C vii RRC, we find \( kT \approx 0.01 \) keV, consistent with low-temperature (\( \lesssim 10^5 \) K), photoionized gas. Based on the ratios of the \( f \) and \( j \) lines from He-like O vii and the relative strength of N vii/f, we suggest that the gas is in the low-density regime (\( n_e \lesssim 10^6 \) cm \(^{-2} \)). We have been able to fit the observed emission-line ratios with a single-zoned photoionization model, with \( N_H = 1.5 \times 10^{21} \) cm \(^{-2} \) and \( U = 1.1 \); however, in the case of solar abundances, the N vii and N viii lines are significantly underpredicted. Hence, we suggest that the N/H ratio is at least 2.5 times solar, which may be the result of secondary production of nitrogen in intermediate-mass stars. Follow-up observations of the stellar population in the nucleus of NGC 3516 could help test this possibility.

3. In order to produce the observed O vii line fluxes, the emission-line gas must have a global covering factor of \( \sim 0.5 \). The scaled (predicted) O vii \( \lambda \lambda 1032, 1038 \) emission is slightly higher than that seen in the FUSE spectrum, although the O vii line ratios and profiles show strong evidence for absorption, possibly from an additional component of UV absorption near the systemic velocity that cannot be deconvolved from the strong UV components seen in the STIS spectra. Hence, the X-ray model is generally consistent with the FUSE spectrum.

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