SUPERSOLAR METALLICITY IN THE NLS1 GALAXY MARKARIAN 1044

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ABSTRACT

We present measurements of the metallicity of the circumnuclear gas in the narrow-line Seyfert 1 (NLS1) galaxy Markarian 1044 using O VI column density measurements from the Far Ultraviolet Spectroscopic Explorer (FUSE) together with C IV, N V, and H I measurements from the Hubble Space Telescope (HST). From the absorption lines we find that the circumnuclear gas in Mrk 1044 has a metallicity of at least 5 times solar, consistent with the expectation from previous emission-line studies that NLS1s have a high metallicity, similar to that found in high-redshift quasars. More surprisingly, we find that the absorbing material requires a near-solar mixture of elements in which the N/C ratio is consistent with the solar ratio and does not scale with the metallicity. This suggests that the chemical enrichment scenario for this active galactic nucleus (and thus possibly others) may be different from the traditional model of galactic metal enrichment, at least in the high-metallicity regime.

Subject headings: galaxies: abundances — galaxies: Seyfert — quasars: absorption lines — quasars: emission lines — quasars: individual (Markarian 1044) — ultraviolet: galaxies

Online material: color figures

1. INTRODUCTION

The study of metallicity, or more precisely, the study of metallicity indicators in active galactic nuclei (AGNs) has a long history (e.g., Bahcall & Kozlovsky 1969). The metallicity of gas in an AGN has the potential to tell us about the star formation history without looking at the stars themselves, which is very important in objects such as high-redshift quasars where what appears to be solar or higher metallicity must have been achieved in less than a gigayear. Metallicity studies have also been conducted on local AGNs, the less luminous Seyfert galaxies. While some may consider the enrichment questions less fundamental in this type of AGNs, there are still curious correlations between the metallicity of (host) gas and the AGN luminosity (Shemmer & Netzer 2002). While standard Seyfert galaxies may have perfectly reasonable metallicity indicators for their host, there are some local AGNs with what appears to be unusually high metallicities: narrow-line Seyfert 1 galaxies.

The AGNs of the narrow-line Seyfert 1 (NLS1) class are distinguished by their relatively narrow permitted lines (<2000 km s⁻¹) and a weak [O III]/Hβ ratio (<3) (Osterbrock & Pogge 1985). Their spectral properties place them at one end of a distribution of AGN properties known as eigenvector 1 (Boroson & Green 1992). Later studies of their X-ray properties found that their steep X-ray slopes as compared to other AGNs (Grupe et al. 2004; Mathur & Grupe 2005). NLS1s and high-redshift quasars both share steep X-ray slopes as compared to other AGNs (Grüpe et al. 2005). Another difference between narrow-line and broad-line Seyfert galaxies is that the emission-line metallicity indicator N v/C IV is much stronger in NLS1s (Shemmer & Netzer 2002). If the N v/C IV ratio is a reliable metallicity indicator, NLS1s should be placed alongside the high-luminosity (high-redshift) quasars as the most metal-rich of all AGNs. While it is not necessarily expected that NLS1s and quasars have similar star formation histories, there is no a priori reason why NLS1s and broad-line Seyfert galaxies should share one. It has been proposed by Mathur (2000a) that NLS1s are an evolutionary phase, and if so, studying their metallicity may inform us as to the evolutionary properties of their host. Even if this hypothesis is invalid, and NLS1s are simply a distinct class of intermediate-luminosity AGNs, then studying the metallicity is important for efforts to distinguish why certain bulges host NLS1s instead of broad-line Seyfert galaxies.

At issue is whether the metallicity indicators traditionally employed do in fact measure the correct metallicity. Unlike in stars, where the physical conditions, input spectrum and localization of various lines are relatively well understood, very little is known about AGNs. The paucity of lines and the fact that they may arise from distinct regions of the AGN with very different
physical conditions adds complications. In addition, historical metallicity studies have in large part used emission lines, for the simple reason that these were all that were available or feasible. And on an order of magnitude basis, a stronger emission line should correspond to a higher abundance of a particular species. Thus, line ratios should give information about the relative quantities of particular elements. Unfortunately, this can be muddied by the shape of the ionizing spectrum or lines coming from physically separate regions (to name two likely problems). Absorption-line studies, being insensitive to effects such as geometry or density, offer a better means to measure of the abundance of a species. While AGN absorption-line studies to investigate metallicity/abundance relationships are typically not feasible for surveys (due to the need for higher resolution spectra than emission-line studies), a few detailed analyses of individual systems have the potential to provide a test of the validity of the much more readily observed emission-line indicators.

In this paper we seek to measure the relative (and absolute) abundances for a few common elements in the NLS1 galaxy Markarian 1044, and we present new observations of this nearby AGN ($z = 0.01645$) with Far Ultraviolet Spectroscopic Explorer (FUSE) satellite. Even with absorption-line studies, however, the ionization correction remains a major problem in transforming the observed ionic column densities to a true abundance. This problem is relatively common in any study that covers a small wavelength region only and/or contains information on few or one species of a particular element. For this reason, we extend the baseline of observed species in Mrk 1044 by adding O vi in the far-ultraviolet range to previous measurements made in a Hubble Space Telescope (HST) study using the Space Telescope Imaging Spectrograph (STIS) at approximately the same epoch (Fields et al. 2005, hereafter F05). Neither data set alone can break the inherent degeneracies in making the photoionization correction, but both data sets together select a small region of parameter space from which we can determine the metallicity of this system. In §2 we detail the observations made and the data reduction path followed. In §3 we give the methods with which we analyze the data. We finish in §4 with our conclusions.

2. OBSERVATIONS AND DATA REDUCTION

Mrk 1044 was observed by the FUSE satellite on UTC 2004 January 1 and 2. The observation was conducted over one ~7 hr series of exposures from MJD 53,005.74609375 to 53,006.046875. The data sets are D0410101. The received data were reduced by the standard CalFUSE pipeline (ver. 2.4.1). The FUSE IDL tool fuse_register was used to cross-correlate, weigh, and coadd the spectra. We use the observations with the 1A detector segment and the LiF mirror (987–1082 Å) in this analysis, as it contains the data we wish to analyze and is the least noisy of the eight FUSE detector segments. To achieve the necessary signal-to-noise ratio (S/N), the LiF 1A spectrum is binned by a factor of 10. The resulting spectrum has a pixel size of ~20 km s$^{-1}$ (the FWHM of the instrument) and S/N's of 3–4 at the continuum, 10–11 at the peaks of the emission lines, and approximately 1.5–3 in the troughs of the strongest absorption lines. In all seven other segments, the FUSE spectra are extremely noisy (S/N ≈ 1.5 at the continuum) and/or do not contain usable information.

The UV spectrum observed by FUSE is shown in Figure 1. The continuum is essentially flat, with a slope indistinguishable from zero (expressed as $\alpha = 0.0$ in $f_\lambda \propto \lambda^{-\alpha}$). While the FUSE spectra from the other channels do not give us much useful information, they do confirm that the flatness of the continuum observed in the LiF 1A channel extends from 920 to 1180 Å. The source has two emission-line complexes, the most obvious being the blend of Ly$\beta$ and O vi $\lambda\lambda 1032, 1038$ observed from 1030 to 1060 Å. The other, much weaker one is N iv $\lambda 1549, 1550$ observed shortward of 1010 Å. There are also many absorption lines, most of which are Galactic in origin, but some of which are intrinsic to Mrk 1044.

Before the data can be analyzed for absorption systems of any sort, the pseudocontinuum (continuum+emission lines) must be modeled. The emission lines were first fit using standard Gaussians. The discussion of the line properties is reserved for its own section (§3.2). This technique failed, however, to fit the profile of the emission lines so as to result in a well-modeled pseudocountinuum. Because the profile of the emission lines was sufficiently non-Gaussian, we instead fitted by eye a spline to the emission-line structure and used this to normalize the spectrum (divided through such that the resulting spectrum nominally varies between zero and one).

3. ANALYSIS

We performed two separate analyses on the absorption-line data. The first was a standard line fitting, which gives us the observational parameters (equivalent width, centroid, line width) and terminates in the estimation of the column density via the curve-of-growth technique described in Spitzer (1978). The second consisted of directly integrating over the line structure to give us the column density via the apparent optical depth technique described by Savage & Sembach (1991). Comparing the results of these two separate methods gives us additional insight into whether these lines yield trustworthy results. Even though studies such as Arav et al. (2005) have found that some absorption features result from inhomogeneous systems, we feel

\footnote{See http://fuse.pha.jhu.edu/analysis/calfuse.html.}
confident in the utility of these methods. The reason for our trust can be found in the *HST* spectra of Mrk 1044. In the F05 study, one can see two distinct absorption systems. System 1 is well sampled and is well fit by a Gaussian profile across the entire line. The quality of such a simple model fit implies that we are dealing with a kinematically simple system (a single absorber). The analysis of lines in our *LUSE* spectrum associated with system 1 should then be unaffected by possible inhomogeneities. System 2, however, exhibits weak lines and has much more noise in its profile, and as a consequence we do not have the data to make the same argument in favor of a single absorber. Our analysis in § 3.3 is focused on lines associated with system 1 and we touch but briefly upon lines of system 2, so we do not anticipate that our conclusions will be adversely affected.

The spectra were normalized in the analysis package LINER (Pogge & Owen 1993), a stand-alone software tool for the analysis of astronomical spectra. We also used LINER to derive initial estimates of the properties of the emission and absorption lines. The resulting fits of this program were then used as the inputs for the STSDAS SPECFIT package (Kriss 1994), which returned the final values of the equivalent widths, line centroids, and line widths, along with the associated errors (from the $\chi^2$ surface). LINER was used for the initial analysis on account of its flexibility and interactive nature, which allowed us to quickly and easily determine the approximate parameters of the feature in question. SPECFIT was used to provide the final values of the parameters because of its accurate and precise fitting near the global minimum due to both the variety of geometrical shapes it fits with and the multiple $\chi^2$ minimization algorithms it has available to help avoid the solution stalling in local minima. Equivalent widths were converted into column densities through the curve-of-growth method. We calculated the column density for velocity spread parameter $b$-values of 10, 20, 40, and 80 km s$^{-1}$, but we report only the value derived from $b = 20$, as that value gives consistent results between the O vi doublet and was also the value used in F05. The line centroiding is limited by localized detector distortions. The Galactic absorption lines show that the absolute velocities should be shifted positively by about 3–5 km s$^{-1}$, while the *LUSE* White Paper on the subject shows that the relative wavelength errors where our lines are located are about 8 km s$^{-1}$. We use this as our centroiding error.

To determine if the apparent optical depth method is appropriate, the first test is whether a line is resolved ($\Delta \lambda_{\text{obs}} > 2\Delta \lambda_{\text{inst}}$). We compared *LUSE*’s instrument profile of $\sim$20 km s$^{-1}$ (FWHM) with the line widths found by the SPECFIT package. A stricter test is for the line to be definitively resolved, i.e., more than 3 standard deviations above the nominal resolution limit. If a line passes these tests, we use the normalized residual flux ($I_r$) that results from the LINER pseudocontinuum fit and integrate over the line.

We have determined two major sources of uncertainty in our line parameters. The first is the standard photon noise one expects that can be propagated through each stage of the analysis process. The second is uncertainty associated with a suboptimal fit to the pseudocontinuum. We determine this by making nine by-eye spline fits in LINER to the emission-line complex. These nine fits resulted in nine different final values of each line parameter. We take the mean of each set as the “best” determination of that parameter. The scatter around that mean is then used as the second component of our uncertainty. In all cases, the fit to the pseudocontinuum is reasonable, but several were purposefully fit to the outer envelope of the noise. The two components of the uncertainty are then added in quadrature to give the final value of the uncertainty provided in this paper.

### 3.1. Galactic Absorption Lines

While the focus of this paper is the absorption lines intrinsic to Mrk 1044, the analysis of those lines is complicated by the presence of many Galactic interstellar medium (ISM) absorption lines. As many absorption lines in an AGN spectrum are the result of outflowing material with velocities high relative to the systemic line identification must begin with locating known Galactic lines so as to avoid contamination. Most of the Galactic absorption is from molecular hydrogen ($H_2$). We use the template of Romano et al. (2002) to model the $H_2$ absorption lines.

The identification of the Galactic metal absorption lines in our spectrum followed from Sembach (1999). For the physical properties of the metal lines we used the National Institute of Standards (NIST) Atomic Spectra Database, as well as the compilation of Morton (2003). The metal lines found are C ii $\lambda\lambda1036, 1037$, O i $\lambda\lambda1303, 1048$, and Fe ii $\lambda\lambda1055, 1063$.

The expected O vi $\lambda\lambda1032, 1038$ doublet was not found, likely due to noise in that spectral region. A satisfactory fit to the $H_2$ absorption would have allowed us to deblend and characterize several other lines, both Galactic and intrinsic to Mrk 1044. Unfortunately, the $H_2$ fitting was never satisfactory. When the weaker $H_2$ lines were fit, the template predicted completely black cores for the strong lines, which were not reproduced in the data. Related to this is the issue that the model’s strong lines have wings that are too weak. Increasing the model column density to fit the wings of the data again produced black cores, but conversely fitting to the core of the strong lines “created” two false absorption lines at the wings out of the residuals. The blackness issue may be caused by the data. All the strong absorption lines (most of them $H_2$) reach a minimum around 0.15, which may indicate a miscalibration in the flux. Supporting this is the Galactic Ly$\beta$ absorption, which fails to reach zero flux (as would be expected from such a strong transition). However, the troughs of all these lines are already (individually) consistent with zero within the errors. Also, resetting the flux at a smaller value does nothing to solve the wings issue because all of these lines lack multipixel flat troughs (which fitting to the wings predict). One possible solution is multiple velocity components in $H_2$, which would act to broaden the absorption. To further investigate this, we rebinned the data by only a factor of 3 (instead of 10), giving us a spectrum with approximately 3 pixels per resolution element. This does not suggest a multicomponent ISM within the bounds of our noise. Because of these problems, we caution against trusting the $H_2$ subtraction, which will affect the characterization of any of the lines that molecular hydrogen is blended with: Galactic C ii and C iii at 1036 and 1037 Å and the Ly$\beta$ line of the stronger system in Mrk 1044 (discussed in § 3.3). Ultimately, we chose to fit to the isolated weak $H_2$ lines, such as those around 1041 and 1054 Å. This fits the largest number of $H_2$ lines at a mediocre level, even if the fit for a few others (the strong $H_2$ lines) is very poor. This choice has the least impact upon our subsequent analysis, because the strongest $H_2$ lines are not blended with the absorption lines of interest to us here.

The properties of the ISM lines found in this *LUSE* LiF 1 A spectrum are listed in Table 1. This table lists the ions, their rest and observed wavelengths, FWHM, equivalent width, column densities via the two methods, and the centroid velocity (relative to zero). We also give the value of the $H_2$ column density as fit to the weak absorption lines. The two C ii lines are blended with $H_2$, C iii especially, and the fit was unstable in SPECFIT. These lines

6 At http://physics.nist.gov/PhysRefData.
are characterized by poor determinations of their physical parameters. For example, the centroid velocity of C \textsuperscript{n} is very inconsistent with zero, indicating that the deblending was unsatisfactory. Because of the deblending problem, we do not provide column density measurements for either of the C \textsuperscript{n} lines. We do provide the measurements of the physical parameters (EW, FWHM, \textit{v}_{\text{rel}}) in the table along with their large uncertainties to illustrate the extent of the effects of the deblending. The redward Fe \textsuperscript{ii} line (\textlambda 1063 Å) is blended in its wings with H\textsubscript{2}, which impairs our ability to successfully match line parameters. Regardless, the two Fe \textsuperscript{ii} lines match well in velocity and column density, matching best at a \textit{b}-value of 20 km s\textsuperscript{-1}, which is near the width of the blueward line. Their FWHM are a very poor match, but that may be due to the deblending fit performed on the redward line. The FWHM are consistent at the 3 \textsigma level, due primarily to the uncertain deblending of the redward line. The O \textsuperscript{i} line appears to be definitively resolved, so we give its column density via the apparent optical depth method. If we choose the same \textit{b} parameter as the one that matches best between the Fe \textsuperscript{ii} lines, we get consistent answers between the curve-of-growth method and the apparent optical depth method. What is not explained, however, is the inconsistency between the two elements’ FWHMs. It should be noted that O \textsuperscript{i} \lambda 1302 as found in F05 has contradictory parameters. As mentioned in that study, O \textsuperscript{i} \lambda 1302 is found in the low-resolution G140L spectrum and is possibly a blend. One should also note that the four lines with column density measurements (O \textsuperscript{i}, Ar \textsuperscript{i}, and both Fe \textsuperscript{ii}) have a velocity consistent with zero, while the two C \textsuperscript{n} lines have the most discrepant velocities and are also the lines most heavily velocity consistent with zero, while the two C \textsuperscript{n} lines are characterized by poor determinations of their physical parameters. For example, the centroid velocity of C \textsuperscript{n} is very inconsistent with zero, indicating that the deblending was unsatisfactory. Because of the deblending problem, we do not provide column density measurements for either of the C \textsuperscript{n} lines. We do provide the measurements of the physical parameters (EW, FWHM, \textit{v}_{\text{rel}}) in the table along with their large uncertainties to illustrate the extent of the effects of the deblending. The redward Fe \textsuperscript{ii} line (\textlambda 1063 Å) is blended in its wings with H\textsubscript{2}, which impairs our ability to successfully match line parameters. Regardless, the two Fe \textsuperscript{ii} lines match well in velocity and column density, matching best at a \textit{b}-value of 20 km s\textsuperscript{-1}, which is near the width of the blueward line. Their FWHM are a very poor match, but that may be due to the deblending fit performed on the redward line. The FWHM are consistent at the 3 \textsigma level, due primarily to the uncertain deblending of the redward line. The O \textsuperscript{i} line appears to be definitively resolved, so we give its column density via the apparent optical depth method. If we choose the same \textit{b} parameter as the one that matches best between the Fe \textsuperscript{ii} lines, we get consistent answers between the curve-of-growth method and the apparent optical depth method. What is not explained, however, is the inconsistency between the two elements’ FWHMs. It should be noted that O \textsuperscript{i} \lambda 1302 as found in F05 has contradictory parameters. As mentioned in that study, O \textsuperscript{i} \lambda 1302 is found in the low-resolution G140L spectrum and is possibly a blend. One should also note that the four lines with column density measurements (O \textsuperscript{i}, Ar \textsuperscript{i}, and both Fe \textsuperscript{ii}) have a velocity consistent with zero, while the two C \textsuperscript{n} lines have the most discrepant velocities and are also the lines most heavily blended with H\textsubscript{2}.

3.2. Mrk 1044 Emission Lines

While this paper is primarily focused on the absorption-line results, we have also measured the UV emission lines so as to estimate Mrk 1044’s metallicity using the traditional emission-line diagnostics. The parameters for the observed emission lines are given in Table 2. Given for each line (Ly\textbeta, N \textit{m}, and O \textit{vi}) are the equivalent widths, the Gaussian FWHM for any components they have, and the velocity offset from systemic (4932 km s\textsuperscript{-1}).

We use the systemic velocity as listed in the NASA/IPAC Extragalactic Database (NED) and taken from the Third Reference Catalogue of Bright Galaxies (RC3; de Vaucouleurs et al. 1995). Henceforth, quoted velocities for components (emission and absorption) intrinsic to Mrk 1044 are given relative to this velocity. In general, the emission lines are offset by hundreds of km s\textsuperscript{-1} blueward, though there does not appear to be a consistent velocity offset among the emission lines. The N \textit{m} doublet is weak enough so as to be fit with a single Gaussian each, while the O \textit{vi} doublet requires a narrow and broad component each. The Ly\textbeta line only requires a broad line; a narrow line does not significantly improve the overall fit. In general, Gaussians adequately, but not well, fit the data. If left completely unconstrained the model of the emission lines returned very unphysical results with regards to the O \textit{vi} doublets, with both narrow components settling between the two broad components or vice versa. To ameliorate this, for each doublet the naturally weaker of the lines is pinned to the stronger. We constrain the width and the wavelength, but leave the relative fluxes unpinned because otherwise the model cannot even adequately fit the data. Due to the absence of a narrow component to Ly\textbeta and because it is blended with O \textit{vi}, one may ask if it is properly identified. Evidence in favor of such an identification is (1) a four-component fit to the O \textit{vi} complex (two narrow and two broad) always leaves an excess of blueward flux; (2) a six-component fit (three per O \textit{vi}) is not sufficiently superior to a broad Ly\textbeta+four-component O \textit{vi}; and (3) the centroid of the component blueward of the O \textit{vi} is generally consistent with the redshift of the other emission lines (Ly\textbeta and N \textit{m}).

3.3. Mrk 1044 Absorption-Line Systems

With the pseudocontinuum normalized and the Galactic lines identified, we constructed velocity maps, with each associated with a particular atomic transition and shifted to the systemic velocity of Mrk 1044. These velocity maps, our Figure 2, cover the same ranges shown in Figure 3 in F05. Our figure shows the likely counterparts to the absorbing systems found by F05 for Mrk 1044, and both Fe \textsuperscript{ii} doublets, with both narrow components settling between the two broad components or vice versa. To ameliorate this, for each doublet the naturally weaker of the lines is pinned to the stronger. We constrain the width and the wavelength, but leave the relative fluxes unpinned because otherwise the model cannot even adequately fit the data. Due to the absence of a narrow component to Ly\textbeta and because it is blended with O \textit{vi}, one may ask if it is properly identified. Evidence in favor of such an identification is (1) a four-component fit to the O \textit{vi} complex (two narrow and two broad) always leaves an excess of blueward flux; (2) a six-component fit (three per O \textit{vi}) is not sufficiently superior to a broad Ly\textbeta+four-component O \textit{vi}; and (3) the centroid of the component blueward of the O \textit{vi} is generally consistent with the redshift of the other emission lines (Ly\textbeta and N \textit{m}).

| Ion | \textlambda_{\text{rest}} (Å) | Equivalent Width (mÅ) | FWHM (km s\textsuperscript{-1}) | Velocity (km s\textsuperscript{-1}) |
|-----|-----------------|------------------|-----------------|-----------------|
| N \textit{m} | 992 | 0.68 ± 0.15 | 341 ± 54 | -190 ± 8 |
| N \textit{m} | 992 | 0.55 ± 0.14 | ... | ... |
| H \textit{i} | 1026 | 5.66 ± 3.65 | 3400 ± 1000 | -314 ± 8 |
| O \textit{vi} | 1032 narrow | 3.78 ± 0.53 | 656 ± 45 | -494 ± 8 |
| O \textit{vi} | 1032 broad | 25.7 ± 5.1 | 3720 ± 480 | -880 ± 8 |
| O \textit{vi} | 1038 narrow | 6.10 ± 0.60 | ... | ... |
| O \textit{vi} | 1038 broad | 13.1 ± 4.8 | ... | ... |

TABLE 1

| Line | Observed Wavelength (Å) | FWHM (km s\textsuperscript{-1}) | Equivalent Width (mÅ) | log (column)a | log (column)b | Velocity (km s\textsuperscript{-1}) |
|------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| C \textsuperscript{n} \l 1036.337 | 1036.2431 | 83.9 ± 10.0 | 263 ± 33 | ... | ... | -27 ± 8 |
| C \textsuperscript{n} \l 1037.018 | 1036.8348 | 236 ± 53 | 610 ± 180 | ... | ... | -53 ± 8 |
| O \textit{i} \l 1039.230 | 1039.2248 | 53.5 ± 4.2 | 183 ± 13 | 15.75 ± 0.10 | 15.56 ± 0.06 | -2 ± 8 |
| Ar \textit{i} \l 1048.220 | 1048.2090 | 17.8 ± 4.5 | 93 ± 14 | 13.73 ± 0.10 | ... | -3 ± 8 |
| Fe \textsuperscript{ii} \l 1055.261 | 1055.2443 | 25.0 ± 4.8 | 58 ± 12 | 15.06 ± 0.12 | ... | -5 ± 8 |
| Fe \textsuperscript{ii} \l 1063.176 | 1063.1610 | 72 ± 17 | 213 ± 41 | 15.16 ± 0.30 | ... | -4 ± 8 |
velocity study: the feature at about $-200 \text{ km s}^{-1}$ appears to be an absorbing system in all but N\textsc{iii} $k_{990}$. However, what could be the O\textsc{vi} $k_{1032}$ line at $z = 0.01578$ is actually Ar $\lambda 1048$ at $z = 0.0$. Another way in which Galactic absorption affects our spectrum is the Ly$\beta$ at the redshift of System 1 which is heavily blended with the 1048 Å H$_2$ line. This figure also shows what is missing: no N\textsc{iii} absorption lines are present at the positions of systems 1 or 2, and no Ly$\beta$ is found at system 2. We note that there appears to be an absorption system at $v \approx 0 \text{ km s}^{-1}$ in the Mrk 1044 frame in O\textsc{vi}. The Ly$\beta$ spectrum at that velocity neither supports nor opposes such a determination. Curiously, while F05’s Figure 3 clearly shows that neither C\textsc{iv} nor N\textsc{v} have absorption at that velocity, its Ly$\alpha$ is consistent with the presence of an absorber. It is possible that this is a highly ionized system, but because we cannot extract reliable information about this unconfirmed absorption system due to the scarcity of its absorption lines, we do not consider it further.

We report good ($>3 \sigma$) detections of four lines belonging to absorption systems intrinsic to Mrk 1044. We find a velocity for system 1 of $-1158 \text{ km s}^{-1}$ and a velocity for system 2 of $-286 \text{ km s}^{-1}$ relative to the systemic velocity of Mrk 1044. These lines are at exactly the same velocities as the systems found in F05. The velocities of each individual line also match well with the mean velocities. In system 2, the weaker of the O\textsc{vi} lines is not detected at $>3 \sigma$. Table 3 gives the measured and calculated parameters for these absorption systems: the observed wavelength, the FWHM, the equivalent widths, the calculated column densities (by both the curve-of-growth and apparent optical depth methods) and the velocity offset from the systemic. For the lines that are not resolved (system 2’s) we give only the column density derived from the curve-of-growth method. For system 1 we also give the apparent optical depth column density, though it should be noted that only the O\textsc{vi} lines are definitively resolved ($>3 \sigma$ above the $2\Delta\lambda_{300}$ limit, which is about 40 km s$^{-1}$). Additionally, the 3 $\sigma$ upper limits on the undetected N\textsc{iii} lines are given.

To determine the column densities with the apparent optical depth method, we first calculated the covering fraction ($C_f$) of each of these two systems following Hamann et al. (1997). However, there is a problem in that O\textsc{vi} $\lambda 1038$ ($I_1$ in their formalism) has a smaller normalized flux value in its trough than O\textsc{vi} $\lambda 1032$ ($I_2$), on average about 0.10 to 0.15, respectively. This is illustrated in Figure 3. This is unphysical, and we attempted to solve this problem by modifying the lines as follows. We note that the uncertainties on data points in the absorption troughs of these lines are about 0.05, and so we calculate two covering fractions, one where the trough of $I_2$ was decreased by 1 $\sigma$, and one where the trough of $I_1$ was increased by 1 $\sigma$. Doing so gave us seemingly reasonable values of the covering fraction, around 0.91 and 0.86, respectively. The first method (decreasing $I_2$), however,

![Velocity maps centered on the velocity of the absorption systems found in F05. System 1 (left) at $-1158 \text{ km s}^{-1}$ and system 2 (right) at $-286 \text{ km s}^{-1}$ match well with the velocities of $-1158$ and $-286 \text{ km s}^{-1}$ found in F05. The line seen in Ly$\beta$ for system 1 is a blend of Ly$\beta$ and a Galactic H$_2$ line.](image-url)
still failed for the majority of our pseudocontinuum normalizations. The second method (increasing $I_1$) mostly succeeded (the O vi $\lambda 1032$ $C_2 + I_{\text{rough}} = 1$ in two of the nine normalizations), so we used this method to determine our covering fraction. We set our integration limits where the flux clearly deviated from the continuum. Figure 3 illustrates this happening between velocities of about $-1110$ and $-1190$ km s$^{-1}$. While the O vi $\lambda 1032$ Å line has an uncertainty on its column density even greater than its value, it should be noted that it matches the column density determined from the other line well. The covering factor for system 2 is, by the formalism, set to 1 since $I_2 < (I_1)^2$. While this is also unphysical, such a result is not unexpected due to this system being unresolved, let alone minimally detected. This result tells us that we have no information about the covering fraction for this line.

The value of the covering fraction for system 1’s O vi is different than that found for C iv and N v. As just given above, we find a covering factor of $\sim 0.86$ for O vi, while the covering factor for the other metal lines is $\sim 0.72$. This could be due to the stratified nature of the broad-line region (BLR), in which O vi emission lines are produced closer to the central black hole than the C iv and N v emission lines. The absorbing gas (system 1), being of finite size, will likely completely cover the continuum source, mostly cover the O vi emitting region, and cover less of the C iv- and N v-emitting regions. Since this simple toy model could explain the observed covering fraction for these three species and because of other similar cases (UM 675 described in Hamann et al. 1997), we do not consider this discrepancy in covering fraction a problem to be corrected.

There is one major caveat that must be addressed with regard to the measurement of the Ly/β line of system 1, namely, that this line is heavily blended with a Galactic H2 line. This is demonstrated by Figure 4, which shows the nine pseudocontinuum fits, before and after the H2 subtraction. The accuracy of the derived H i column density is strongly dependent on the quality of the H2 subtraction and reflected in the larger uncertainties of our Ly/β measurements compared to the other absorption lines. What is not reflected in these uncertainties is systematic effects, such as a

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**TABLE 3**

| Line       | Observed Wavelength (Å) | FWHM (km s$^{-1}$) | Equivalent Width (mA) | log (column) (cm$^{-2}$)$^a$ | log (column) (cm$^{-2}$)$^b$ | Velocity (km s$^{-1}$) |
|------------|-------------------------|-------------------|------------------------|-----------------------------|-----------------------------|------------------------|
| Ly$γ$      | 984.82                  | ...               | ...                    | <15.00                      | ...                         | ...                    |
| Lyβ        | 1038.5757               | 50 ± 12           | 135 ± 37               | 14.69                       | 14.60                       | -1175 ± 8              |
| O vi $\lambda 1032$ | 1044.9335               | 69 ± 3            | 244 ± 14               | ≥15.12 ± 0.16               | 14.93 ± 0.14                | -1153 ± 8              |
| O vi $\lambda 1038$ | 1050.7038               | 61 ± 3            | 210 ± 15               | ≥15.08 ± 0.14               | 14.92 ± 0.14                | -1150 ± 8              |
| N iii $\lambda 990$ | 1002.291                | ...               | ...                    | <14.12                      | ...                         | ...                    |
| N iii $\lambda 992$ | 1004.103                | ...               | ...                    | <14.16                      | ...                         | ...                    |
| C iv $\lambda 1549$ | 1230.9819               | 92 ± 7            | 341 ± 5                | 14.20 ± 0.09                | -1156 ± 7                   | ...                    |
| N v $\lambda 1239$ | 1254.4633               | 71 ± 3            | 209 ± 8                | 14.42 ± 0.02                | -1143 ± 6                   | ...                    |
| N v $\lambda 1243$ | 1258.4999               | 71 ± 3            | 162 ± 6                | 14.51 ± 0.02                | -1143 ± 6                   | ...                    |
| C iv $\lambda 1551$ | 1507.3602               | 47 ± 5            | 156 ± 4                | 14.04 ± 0.02                | 14.48 ± 0.06                | -1143 ± 5              |

* Derived from the curve-of-growth method with $b = 20$ km s$^{-1}$.
* Derived from the apparent-optical-depth method.
* With 3σ upper limits.
* Possible saturation.
* Values from F05, corrected for error in $C_r$.

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**Fig. 3.**—Velocity structure of the O vi doublet relative to the systemic velocity of Mrk 1044. The solid line traces O vi $\lambda 1032$, while O vi $\lambda 1038$ Å is traced by the dotted line. The dotted-line feature at $-1050$ km s$^{-1}$ is a $z = 0$ H2 absorption line. The line at flux = 1 represents the continuum of a perfect normalization and is provided for comparison. The data are binned to the FWHM of the instrument.
blueshift in the Ly$\beta$ line by about 3 times the wavelength uncertainties. Compared to the Ly$\alpha$-derived H i column densities from F05, the Ly$\beta$-derived value is a factor of 2–4 larger. If the Ly$\alpha$-value is correct, the H$_2$ line blended with Ly$\beta$ is likely undersubtracted. In this case, our Ly$\beta$-derived value should represent an upper limit on the total H i column. However, increasing the strength of the H$_2$ line shifts the Ly$\beta$ line to an even more discrepant centroid. The disagreement between these two Lyman lines could be resolved by an observation of higher order Lyman series lines, such as Ly$\gamma$, but those lie outside the range of the LiF 1A channel. The SiC 2B channel has nothing, and while the SiC 2A channel has a slight depression at the appropriate wavelength for Ly$\gamma$, the entire “line” is only a 1 $\sigma$ or 1.5 $\sigma$ detection. With no guidance from other Lyman series lines, we must instead assess which line, Ly$\alpha$ or Ly$\beta$, is more trustworthy. As Figure 4 of F05 shows, the Ly$\alpha$ line is symmetric and appears clean of contamination from coincident lines. Its profile does not suggest saturation, and the surrounding continuum is well-normalized. This paper’s Figure 4 shows a very asymmetric Ly$\beta$ line, and the normalization is not nearly as well determined. We therefore adopt the Ly$\alpha$ line as the measure of the H i column density. Even so, we also wish to point out that if the Ly$\beta$ line is taken as the fiducial line, this changes our results only in magnitude, not in quality, as we see in § 4.

To determine the elemental column densities from the ionic column densities, we must make an ionization correction. To do so, we used the photoionization-equilibrium code CLOUDY 947 (Ferland et al. 1998). This code creates a model of gas in equilibrium with a photoionizing flux. From this, we took the predicted column densities of various species for specific input conditions and compared them with the data. The four relevant inputs to CLOUDY are (1) the incident spectral energy distribution (SED), (2) $U$, the ratio of the number density of ionizing photons to particle (H) density at the surface of the modeled cloud, (3) the abundance ratios in the gas cloud, and (4) $N_{\text{H}}$, the column density of hydrogen through the cloud. Our analysis method was to select a limited set of metallicity and SEDs, over which we then varied $U$ and $N_{\text{H}}$ to create a series of two-dimensional simulation grids. Our analysis was primarily based

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**Fig. 4.—Ly$\beta$+H$_2$ blend.** Normalized (flattened) spectra in the velocity space of the Ly$\beta$ line relative to the systemic velocity of Mrk 1044 are shown for all nine spline fits to the pseudocontinuum. The solid line is the spectrum after normalization but before H$_2$ was subtracted, whereas the dotted line shows the spectrum after the subtraction has taken place. The postsubtraction error bars are shown in the bottom left panel and are representative of all nine fits. Horizontal lines at flux $= 1$ are provided to represent the continuum in a perfect normalization.
SUPERSOLAR METALLICITY IN MRK 1044

Fig. 5.—CLOUDY models using its AGN template spectrum at many log $U$--log $N_{\text{HI}}$ points, assuming solar metallicity. Shaded regions indicate agreement with observed column densities at the 1 $\sigma$ level for several ions. Column densities of H i were calculated for covering factors $C_f = 0.75, 0.85,$ and 1.00. The range of CLOUDY models in agreement (the thickness of the band) with H i is independent of covering fraction for $C_f = 0.80$ and larger. At smaller values of the covering fraction, the precision of our measurement decreases as $C_f$ approaches the depth of the Ly$\alpha$ line ($\approx 0.75$). See Fig. 4 of F05 for an example of the normalized spectrum around Ly$\alpha$. Note that the metal lines all agree in a small region of parameter space around log $U = -1.29$ and log $N_{\text{HI}} = 18.85$. The distance in log $N_{\text{HI}}$ between this point and the preferred model for H i is about $+0.7$, and between the metal-selected model and the 1 $\sigma$ envelope of H i the distance is about $+0.6$. [See the electronic edition of the Journal for a color version of this figure.]

on CLOUDY’s standard AGN template SED and a metallicity of solar in abundance and mixture. The grid of log $U$ and log $N_{\text{HI}}$ input values ranged for log $U$ from $-2$ to 0 and log $N_{\text{HI}}$ from 18 to 20, respectively, with spacing of 0.01. From this we extracted predicted column densities of relevant ions.

We searched for models that predicted ionic column densities in agreement with the O vi observations reported in this paper and the H i, C iv, and N v observations of F05. The C iv and N v column densities reported in F05 were too low because of an incorrect determination of the covering fraction. The correct values are given in the erratum are also reported here. The corrected column densities we will use are log $C_{\text{iv}} = 14.47 \pm 0.06$ and log $N_{\text{Civ}} = 14.46 \pm 0.02$. We compute the column density of H i for a range of covering fraction from 0.75 to 1.00, since an estimate of the true covering fraction cannot be made in the same way as for the doublet lines. The results are shown in Figure 5. In this way each figure point in parameter space that results in a predicted column density that is consistent within 1 $\sigma$ of the observed column density is shaded according to which line is being compared. The thin ribbon of parameter space that denotes a match with the N v column densities can be used to illustrate the interplay between log $U$ and log $N_{\text{HI}}$. At constant log $N_{\text{HI}}$ the total quantity of nitrogen is fixed, but the fraction of nitrogen in the form of N v rises as the number of ionizing photons (log $U$) increases. Eventually, this fraction reaches a maximum and starts to decline because there are so many ionizing photons that most of the nitrogen is N vi, N vii, and N viii. For example, at log $N_{\text{HI}} = 19$, there are two possible physical conditions that produce the observed quantity of N v column density. At smaller values of log $N_{\text{HI}}$, there is less total nitrogen, and eventually there is not enough nitrogen to create the observed column of N v. This example also shows the necessity of observing multiple species. If we only had measurements of N v and log $N_{\text{HI}}$ was 19, we would be unable to tell if log $U$ was low ($-1.75$) or high ($-0.85$). There is no region of parameter space that agrees with all of our observations, but there is a small zone around log $U = -1.29$ and log $N_{\text{HI}} = 18.85$ where all three ionic column densities agree. In this region the fraction of carbon in C iv is in decline due to a high photon flux, the fraction of oxygen in O vi is still limited by the low photon flux, and there is just enough total nitrogen to create the quantity of N v we observe.

We also investigated how the choice of the incident continuum affects our results. The SEDs of two NLS1s (Ark 564 from Romano et al. 2004 and the mean Seyfert SED of Komossa & Schulz 1997 modified to match NGC 4051 as per Komossa & Mathur 2001) were used and produced qualitatively the same result, though the agreement of the three metal lines takes place at the 3 $\sigma$ to 3.5 $\sigma$ level. Compared to Figure 5, all metals shift to more negative log $U$-values, the magnitude of which is highest for oxygen, small for nitrogen and smallest for carbon, about 1.0, 0.5, and 0.3 dex, respectively. Additionally, the amount of H i for a particular log $U$ shifts to smaller values of $N_{\text{HI}}$ by between 0.4 and 0.6 dex. We also decreased the amount of flux emerging in the EUV (as this is an unobservable region of the spectrum) and found that this made a change in properties small compared to that due to SED differences between the CLOUDY table agn and the two NLS1s. We also tested nonsolar abundance mixtures by increasing nitrogen by factors of 2 and 4. We find our data are consistent at the 3 $\sigma$ level with overabundant nitrogen at twice the solar mixture, but inconsistent with 4 times solar.

3.4. Intergalactic Absorption

Following our analysis in F05, we searched our FUSE data for intergalactic absorption lines. In F05 three Ly$\alpha$ forest lines were found (see their Table 5). Assuming no saturation (still on the linear part of the curve of growth), the expected equivalent width of the strongest Ly$\beta$ line would be about 40 mÅ. The 3 $\sigma$ detection in this region is around 100 mÅ, determined from the rms values of the data at the continuum and assuming a 3 pixel wide absorption line. Regardless, there are two absorption features that appear to be the Ly$\beta$ counterparts of the two stronger of the Ly$\alpha$ absorption systems. Ly$\beta$ associated with the weakest of the three Ly$\alpha$ systems is coincident with a blend of Galactic H2 and C ii lines, which, given the problems with deblending described in § 3.1, make its recovery problematic. The other two Ly$\alpha$ systems should have corresponding absorption in Ly$\beta$ at 1033.0 and 1035.8 Å, and we find two systems at 1033.1 and 1035.7 Å with equivalent widths of 105 and 80 mÅ, respectively. By this measure, the weaker line is not definitively detected and the stronger is very close to the nominal 3 $\sigma$ limit. It should be noted that at the location of the stronger line the pseudocontinuum is at an apparent minimum, lying between the O vi emission line and some excess flux that rises toward the blue for about 5 Å (see Fig. 1). The normalization of this region is very uncertain and contributes a 20 mÅ uncertainty to the overall equivalent width. Combined with the photon noise error, this pushes the detection of the stronger of the lines below the nominal 3 $\sigma$ detection limit. While both of these features are at the correct locations to be the Ly$\beta$ counterparts to the low-redshift Ly$\alpha$ forest lines found in F05, the quality of the data is not sufficient to make a definitive confirmation. Were these the Ly$\beta$ lines, their strengths would be much larger than expected but still consistent at the 2 $\sigma$ level (indeed, consistent with zero at the 3 $\sigma$ level). For this reason we
suggest that the Ly$\alpha$-determined values for this system stand as the measurement of these systems.

4. DISCUSSION AND CONCLUSIONS

As discussed in § 3.3, there is no one set of input conditions from which CLOUDY can create a model that reproduces all of the observed column densities of the associated absorption lines. This indicates that one or more assumptions made by these models must be incorrect. The fact that there is a model (log $U = -1.29$ and log $N_{\text{H}} = 18.85$ with the standard CLOUDY AGN SED) that is extremely satisfactory in predicting the column densities of all the metal species, but not that of H i, provides one answer. If the bulk metallicity is in fact about 0.7 dex higher (i.e., log $N_{\text{H}}$ is actually 18.15), then all measured lines (assuming that Ly$\alpha$ has $C_f \approx 0.75$) are in excellent ($< 1\sigma$) agreement. The fact that there is one point that all three metal species agree so well at indicates a good probability of having a solar mixture. With a bulk metallicity around 5 times solar (+0.7 dex), this is inconsistent with a flat trough and there is only a factor of 2 to match the metal's minimum at log $U = -1.29$ and log $N_{\text{H}} = 18.85$. This implies a metallicity of +0.71 and thus a corrected log $N_{\text{H}}$ of 18.14.

Figure 6.—The $\chi^2$ surface for CLOUDY models at solar metallicity compared to observed column densities of H i, C iv, N v, and O vi. The surface is shown up to a $\chi^2$ of 10, and the curves of constant $\chi^2$ (2, 4, 6, 8, and 10) are projected into the log $U$-log $N_{\text{H}}$ plane. The H i component of the fit has been shifted by $-0.71$ dex to match the metal's minimum at log $U = -1.29$ and log $N_{\text{H}} = 18.85$. This implies a metallicity of +0.71 and thus a corrected log $N_{\text{H}}$ of 18.14.

Figure 7.—Same as Fig. 6, but for a bulk metallicity of 5 times solar, with a solar mixture in metals and helium enhanced by $\Delta Y/\Delta Z = 2$. The minimum in this case lies at log $U = -1.20$ and log $N_{\text{H}} = 18.13$, only slightly different than the inferred values from Fig. 6.

solar, log (He/H) $\approx -0.52$. Including this effect does not change our inferred metallicities, but it does shift the best-match log $U$ to slightly higher values. At the increased metallicities, the metal lines come into agreement with the H i, though this point is also at larger values of log $U$ (cumulative with He effects). For the standard AGN SED, we find log $U = -1.20 \pm 0.04$, log $N_{\text{H}} = 18.13 \pm 0.02$, and $Z = 5^{+1}\,_{-2}$ solar metallicities. For the Ark 564 SEDs we find log $U = -1.55 \pm 0.03$, log $N_{\text{H}} = 17.86 \pm 0.02$, and $Z = 17^{+3}\,_{-2}$. For the NGC 4051 SED we find log $U = -1.68 \pm 0.03$, log $N_{\text{H}} = 17.85 \pm 0.02$, and $Z = 22^{+4}_{-1}$.

The $\chi^2$ surface for the standard AGN SED with solar metallicity, but with the H i best-fit point artificially shifted to the best-fit point of the metals, is shown in Figure 6. The $\chi^2$ surface for the standard AGN SED with 5 times solar metallicity (and no shift in H i) is shown in Figure 7. Lines of constant $\chi^2$ are projected into the log $U$-log $N_{\text{H}}$ plane. The smoothness and parabolic shape of the $\chi^2$ surface indicate that we have well sampled the log $U$-log $N_{\text{H}}$ parameter space. We remind the reader that we have used a Ly$\alpha$-derived value of $N_{\text{H}}$, that is much smaller than the Ly$\beta$-derived value. If we instead adopt the Ly$\beta$-value, the inferred bulk metallicity is +0.3 dex (twice solar) using the same arguments, though in § 3.3 we have discussed why Ly$\beta$ should not be used.

This study reinforces the necessity of having a wide range of ionic species to accurately model the physical conditions in these absorbing systems. If we had created the same models as we did in this study, but only using the F05 data and assuming $N \propto Z^2$, we would have concluded that log $U \approx -1.8$, the value that puts N v and H i equidistant from C iv in the log $U$-log $N_{\text{H}}$ plane. While we would still infer a metallicity of approximately +0.7 dex with these data, the physical conditions would be very different and the photoionization correction for other species could be quite wrong. The measurement of the O vi column density determination. There are two basic forms a challenge may take: (1) that the O vi doublet is what allows us to determine a metallicity without the assumption of $N \propto Z^2$. We must therefore assess how our conclusions would change under challenges to the O vi column density determination. There are two basic forms a challenge may take: (1) that the O vi doublet is saturated, in which case we have actually measured a lower limit on the column density; or (2) that our value of the covering factor is too small, in which case the actual column density is likely smaller in magnitude than our calculation.

If the O vi lines are in fact saturated, the degree of saturation is unlikely to be strong. The profiles of the O vi lines (seen in Fig. 3) lack damping wings, the core of the weaker line (O vi $\lambda 1038$ Å) is inconsistent with a flat trough and there is only a factor of 2
difference between the doublet’s optical depths, and the $b$-value of 20 km s$^{-1}$ (common to the metal lines) indicates at most only modest saturation. While the doublet may not be heavily saturated, there is likely to be some degree of saturation in the O $\text{vi}$ 10302 line. The uncertainty on the apparent optical depth–derived column density (see Table 3) of this line is large compared to the value of the line itself. The formal uncertainty in this method behaves in just this manner when the normalized flux $+C_{\tau} \approx 1$, which is true near or at saturation. This saturation is likely not to be heavy, however, as the O $\text{vi}$ 10302 $\lambda$ line shows no such effect and has half the optical depth as the stronger line. If, however, saturation does heavily affect both lines of this doublet, then the band of acceptable models shown in Figure 5 instead represents a lower limit on log $N_{\text{H}}$ for models consistent with the O $\text{vi}$ observations. This region of acceptable models includes the fiducial solution described above, as well as a large class of models with log $U \approx -0.8$ with near-constant values of nitrogen and carbon enrichment of $+0.4$ dex and $+0.6$ dex, respectively. These latter models would suggest that the N/C ratio decreases as the bulk metallicity increases. In terms of prior expectations, this result is even more unusual than our claim of constant N/C at supersolar metallicities. As mentioned, the expectation ($N \propto Z^2$) is only allowed at a lesser value of log $U$ and log $N_{\text{H}}$, which is in a region of parameter space still disallowed even when the measurement of O $\text{vi}$ is considered a lower limit.

If instead we consider that the covering factor has been underestimated, increasing $C_{\tau}$ would decrease the derived column density of O $\text{vi}$. Models consistent with the new column density have smaller log $N_{\text{H}}$ at fixed log $U$. At most, however, we can decrease the column density by a factor of 2 by assuming a maximal covering fraction $C_{\tau} = 1.0$. In this scenario, the best model disagrees with both C $\text{iv}$ and N $\text{v}$ at the 4 $\sigma$ level (O $\text{vi}$ at 3 $\sigma$), making all models with a solar mixture unacceptable. If we relax the solar mixture requirement for nitrogen (but retain it for carbon and oxygen), we can find an acceptable model with a carbon-oxygen enrichment of $+0.66$ dex and a nitrogen enrichment of $+0.87$ dex. While this indicates an enhancement of nitrogen above the solar ratio at a bulk metallicity of $\sim 4.5$ times solar, this enhancement is still not enough to match the expected scaling, instead giving $N \propto Z^{1.3}$. Thus, neither saturation nor too small a covering fraction affects the sense of our conclusion, only its magnitude. In all cases the expectation that nitrogen scales like the square of the bulk metallicity fails for system 1.

We now compare our absorption-line results with emission-line estimates following the formalism of Hamann et al. (2002), noting that the solar mixture used by Hamann et al. (2002) is the earlier, more metal-rich mixture. If the new values for the solar metallicity are used, the metallicities referenced here should be about 0.11 smaller, following Baldwin et al. (2003). The emission-line ratios in common (using this study’s and F05’s corrected values) are N $\text{v}/\text{He ii}$, N $\text{v}/\text{C iv}$, N $\text{v}/\text{O vi}$, and N $\text{v}/(\text{C iv}+\text{O vi})$. We also have a measurement of N $\text{iv}$, but Hamann et al. (2002) find the metallicities derived from it to be discrepant, as do we. We therefore exclude it from this comparison. Ratios involving N $\text{v}$ do surprisingly well, indicating a gas metal-rich by a factor of $+0.7$ to $+0.8$ dex on average, very close to our absorption-line values using the standard AGN SED. It is curious, however, that these emission-line models assume $N \propto Z^2$, which is inconsistent with the absorption-line results, and still give the same bulk metallicity. Compared to the NLS1 SEDs that favor a much higher bulk metallicity, however, the emission-line ratios fare rather poorly.

The results of our absorption-line analysis are somewhat surprising, not because of the supersolar bulk metallicity found (which was already expected), but because of the solar mixture of nitrogen relative to carbon and oxygen. Theoretical models and observations around solar metallicity have nitrogen scaling like $Z^2 \left( [\text{N/O}] \propto [\text{O/H}] \right)$ because the CNO cycle will preferentially convert the other metals over long timescales (Hamann & Ferland 1999 and references therein). One would assume that a local spiral galaxy such as Mrk 1044 would have had constant star formation over the past many gigayears and therefore have nitrogen scaling as $Z^2$. There exists, then, a contradiction between our data and theory. If the analysis of our data is wrong, the extent of the error could be minimized by assuming the fault is limited to the O $\text{vi}$ measurement. Using the F05 data only and assuming $N \propto Z^2$, we find log $U \approx -1.8$ as discussed above. To force agreement with these inferred physical conditions, O $\text{vi}$ must be reduced in column density by a factor of 16. This is statistically unlikely, but there may be a hidden systematic effect that we have not discovered.

Another way in which our analysis might be flawed is that we have assumed a simple absorber in our CLOUDY models. System 1 may in fact be more complicated with a cooler cloud producing the H $\text{i}$, C $\text{iv}$, and N $\text{v}$ absorption embedded in a hotter envelope producing the O $\text{vi}$ absorption. The excellent match in kinematic properties across all the absorption lines makes such a possibility unlikely but cannot completely rule out such a scenario.

If our absorption-line analysis is correct, one way to reconcile data and theory would be to invoke a special enrichment process in the nucleus of Mrk 1044 that would enhance the abundances and mixture to the values we observe. The enrichment scenario in the nucleus of an active galaxy may be very different from that in the larger scale environment of a galaxy as a whole. If this is true, then understanding metallicities in high-redshift quasars should not be based on simple models of metal enrichment in galaxies. Another is that the existing models are simply not appropriate to this system. The theory that predicts N going like $Z^2$ results from studies near solar metallicity. It is fair to say that a metallicity of $+0.7$ to $+1.0$ (such as in Mrk 1044) is a far extrapolation from the data these trends are based on. Additionally, metal mixtures such as we find are not unprecedented for high-metallicity stars. A recent study of planet-bearing and therefore statistically metal-rich stars by Ecuviillon et al. (2004) finds that [N/H] scales with [Fe/H] (the [N/H]/[Fe/H] slope is consistent with zero at the 2 $\sigma$ level) over the range $-0.4 < [\text{Fe/H}] < +0.4$. This study stops well short of the metallicity of Mrk 1044, but this is because the number of significantly supersolar stars simply runs out. Thus, our result can simply be a continuation of an existing observed trend in enrichment. This, like the $N \propto Z^2$ theory, hinges on an extrapolation, though not nearly as large a one. With the dearth of Galactic studies at extremely high metallicities, Mrk 1044 can provide a calibration point not only for AGN metallicity studies but also for enrichment theory.

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