Absorption-Line Measurements of AGN Outflows

Dissertation

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ABSTRACT

Investigations into the elemental abundances in two nearby active galaxies, the narrow-line Seyfert 1 Markarian 1044 and the Seyfert 1 Markarian 279, are reported. Spectra from three space-based observatories *HST, FUSE*, and *CHANDRA*, are used to measure absorption lines in material outflowing from the nucleus. I make multi-wavelength comparisons to better convert the ionic column densities into elemental column densities which can then be used to determine abundances (metallicities).

Narrow-line Seyfert 1 galaxies are known to have extreme values of a number of properties compared to active galactic nuclei (AGNs) as a class. In particular, emission-line studies have suggested that NLS1s are unusually metal-rich compared to broad-line AGNs of comparable luminosity. To test these suggestions I perform absorption-line studies on the NLS1 Markarian 1044, a nearby and bright AGN. I use lines of H I, C IV, N V, and O VI to properly make the photoionization correction through the software Cloudy and determine abundances of Carbon, Nitrogen and Oxygen. I find two results. The first is that Markarian 1044 has a bulk metallicity greater than five times solar. The second is that the N/C ratio in Markarian 1044
is consistent with a solar mixture. This is in direct contradiction of extrapolations from local H II regions which state N/C should scale with bulk metallicity. This implies a different enrichment history in Markarian 1044 than in the Galactic disk.

I also report discovery of three new low-redshift Lyα forest lines with \( \log N_{HI} \geq 12.77 \) in the spectrum of Markarian 1044. This number is consistent with the 2.6 expected Lyα forest lines in the path length to Markarian 1044.

I also investigate the CHANDRA X-ray spectrum of Markarian 279, a broad-line Seyfert 1. I use a new code, PHASE, to self-consistently model the entire absorption spectrum simultaneously. Using solely the X-ray spectrum I am able to determine the physical parameters of this absorber to a degree only slightly poorer than in the multi-wavelength study of Markarian 1044. I find consistency with solar abundance in this Seyfert 1.
Dedicated to my grandfather Ced. A man hard to love, but easy to respect.
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Chapter 1

Introduction

1.1. Gas Abundances in Active Galaxies

In astronomy, one tool we use to understand the evolution of the universe and its component galaxies is the elemental composition of the baryonic gas that pervades it. The abundances of each element are changed by nuclear processes in stars and supernovae. Thus by determining the composition of a gas, we can understand its history. For example, we can tell that the gas that formed the Solar System is a combination of gas that underwent processing in supernovae, gas that was blown off of lower mass stars during their asymptotic giant branch phase, and gas that had not undergone any stellar processing whatsoever and thus must have been extragalactic gas that had recently fallen into the Galaxy. Knowing the composition of the Sun tells us something about the history of the Galaxy up to the time the Sun was formed. In an analogous situation, we can get a window into the history of the gas that makes up an Active Galactic Nucleus (AGN) by studying its composition.
An AGN is the result when interstellar gas accretes onto the supermassive black hole in the centers of galaxies. There are many reasons why one would wish to study the gas in an AGN. The most matter-of-fact is that AGNs can be very luminous objects ($> 10^{45} \text{L}_\odot$) and can thus be used to probe the composition and thence history of gas in the early universe (some AGNs appear less than a Gyr after the Big Bang). The traditional methods of studying the composition of gas in an AGN is to analyze the emission lines, and use emission-line ratios calibrated by photoionization models to reconstruct the abundances of the various elements. This works to a large degree because the larger the abundance of a particular species, the greater the line strength of that species. However, the major problem is that emission-line fluxes are ionization weighted. Our understanding of the broad-line region (BLR; where the emission lines in an AGN originate) is still limited and thus kinematics, a range of densities, and a range of ionization values across the BLR all complicate our conversion from emission-line fluxes to elemental abundances. For this reason, emission lines can be useful for relative abundance estimates, but should not be relied upon to provide an absolute abundances estimate.

The accurate way to measure abundances therefore lies with absorption lines. Absorption-line abundances are insensitive to geometry and density effects such as would be seen in the BLRs of AGNs. What is useful, then, are a few targeted absorption-line abundance studies to calibrate the emission-line studies. However, there are a few challenges that must be faced for a proper absorption-line study to be
faced. The first is that absorption lines, by definition, are produced by intervening clouds of gas. One must find systems that have absorbers in the line-of-sight. The second is that the absorbing material must be kinematically simple. You must be able to deconvolve the kinematics from the absorption profile. The third is that the origin of the absorbing material must be identifiable. Knowing the composition of a gas cloud does not help you if you don’t know if the absorber originates in the host galaxy or is associated with the AGN itself. Fortunately, nature has provided us with a solution: AGN outflows. The powerful luminosity of an AGN ionizes and then frees material from the accretion disk, creating a wind that flows away from the central black hole. This wind can have a significant filling factor ($\gtrsim 10\%$) which means that it will not be difficult to find AGN with outflowing material occulting the central light source. This automatically solves the third problem in that this absorbing material can be easily associated with the AGN. Its ejection kinematics separate it from gas originating in the host galaxy. The measured abundances in the absorbing outflow can then be directly associated with the gas in the AGN, allowing one to directly calibrate the emission-line abundances. The problem is in finding a kinematically-simple outflow. Many AGNs have many superposed velocity components in their outflow (for example, the Broad Absorption Line QSOs or BALQSOs). In addition to having flat absorption troughs these AGNs often have saturation effects which increase the difficulty of extracting information.
There are also some problems associated with transforming the observables into abundances. When we measure absorption lines, we are measuring the column density of a particular ionic species. To get the total true elemental column density from the ionic, we must apply a photoionization correction. Ideally one knows the spectral energy distribution (SED) of the AGN under observation. Without it, we must use a generic SED which has the potential to preferentially suppress or enhance the correction as applied to species with differing ionization potentials. Finally, even if everything else has been done correctly, it is still possible to encounter degeneracies in the photoionization correction, the severity of which can vary across the entire spectrum possible.

1.2. Relation to Previous Work

The study of metallicity (abundance), or more precisely, the study of metallicity indicators in active galactic nuclei (AGNs) has a long history (e.g., Bahcall & Kozlovsky 1969). Studies have been conducted both on the high-redshift quasars (stretching back to times less than a Gyr after the Big Bang), and the local AGNs, the less luminous Seyferts. While some may consider the enrichment questions less fundamental in Seyfert galaxies, there are still curious correlations between the metallicity of the host and the AGN luminosity (Shemmer & Netzer 2002). While standard Seyferts 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 1s.

The AGNs of the narrow-line Seyfert 1 (NLS1) class are distinguished by their relatively narrow permitted lines ($< 2000 \text{ km s}^{-1}$) and a weak $[\text{O III}]/\text{H}\beta$ 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 spectra compared to other Seyfert 1s (Boller, Brandt & Fink 1996; Brandt, Mathur & Elvis 1997) and quasars (Laor et al. 1997) continue to place them at one end of this variation in AGN properties.

It is generally accepted that the physical driver of Eigenvector 1 is the fractional Eddington accretion rate ($\dot{m} = \dot{M}/\dot{M}_{\text{Edd}}$) as suggested by Pounds, Done & Osborne (1995) and Boroson (2002). This would make NLS1s a class of AGNs with a high specific accretion rate, in some ways similar to high redshift quasars (see Mathur 2000b for other ways in which NLS1s and high-$z$ quasars may be similar). Because NLS1s have a similar luminosity distribution to that of broad-line Seyfert 1s, this places the central black hole mass of NLS1s ($10^6-10^7 \text{ M}_\odot$) smaller than those of broad-line Seyfert 1s ($10^8-10^9 \text{ M}_\odot$) (Grupe et al. 2004, and references therein). Well-established relationships between the mass/velocity dispersion of a spheroid and the mass of the central black hole (Gebhardt et al. 2000; Ferrarese & Merritt 2000; Merritt & Ferrarese 2001) suggest that NLS1s may lie in galaxies with weak
bulges. This may not be true in general as there is evidence that some NLS1s may not lie on the standard $M_{BH}-\sigma$ relation (Mathur et al. 2001; Grupe & Mathur 2004; Mathur & Grupe 2005). NLS1s and high-redshift quasars both share steep X-ray slopes as compared to other AGNs (Grupe et al. 2005). Another difference between narrow-line and broad-line Seyferts 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 along 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 Seyferts should share one. It has been proposed that NLS1s are an evolutionary phase by Mathur (2000a) and if so, studying their metallicity may inform us 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 to try and distinguish why certain bulges host NLS1s instead of broad-line Seyferts.

At issue is whether the metallicity indicators traditionally employed do in fact measure the correct metallicity. By studying an individual NLS1 in detail and measuring its abundances with absorption lines, I can simultaneously test the claims that NLS1s do in fact have a significantly super-solar metallicity and therefore differ from their broad-line siblings in another firmly determined parameter, and I can provide an anchor point for the emission-line metallicity indicators. To the extent
that the physical driver of the relatively heavy accretion rate is the same in NLS1s
and high-z QSOs, and it also bears some role in determining the stellar enrichment
pattern, I may also derive some understanding of the metal enrichment in the early
universe.

1.3. Scope of the Dissertation

In this dissertation I present the analysis of three data sets covering two types
of Seyfert galaxies. In Chapter 2 I discuss the near-UV (1200Å-1700Å) spectrum
of the nearby (z = 0.01645) narrow-line Seyfert 1 galaxy Markarian 1044 as taken
by the STIS instrument onboard HST. I will show what limits I can place upon
the abundances with just this information. In Chapter 3 I expand the analysis
of Markarian 1044’s outflow with far-UV data (990Å-1080Å) from the FUSE
observatory. This allows me to directly determine the abundances of the outflowing
gas. Chapter 4 is a re-analysis of the Seyfert 1 Galaxy Markarian 279, using an
archival X-ray spectrum obtained with the CHANDRA observatory combined with
abundances derived from the near-UV spectroscopy of Gabel et al. (2005). In the
final chapter, Chapter 5, I summarize the results of this work and show some natural
directions this research can take in the future.

Chapter 2 contains material drawn from a study published as D. L. Fields, S.
Chapter 2

HST Observations of Markarian 1044

2.1. Introduction

The first target for my absorption-line study is the narrow-line Seyfert 1 Markarian 1044. This NLS1 is nearby (z=0.01645) and bright giving us excellent signal-to-noise. Mrk 1044’s emission lines already suggest the presence of super-solar abundances in the AGN gas which allows us (with an absorption-line study) to test stellar enrichment models in a regime never tested before.

2.2. Observations and Data Reduction

Mrk 1044 was observed on UTC 2003 Jun 28 using the Hubble Space Telescope Imaging Spectrometer (STIS) with the FUV-MAMA detector. All observations were acquired during a single 5-orbit visit that ran from MJD 52818.19912 through MJD 52818.49349. A journal of observations is given in Table 2.1. The 52X0.2 aperture and a clear filter were used for all observations, centering the aperture on the bright nucleus of Mrk 1044. Two low-dispersion UV spectra with the G140L grating (central...
wavelength of $\lambda_{1426}$ Å and spectral resolution of 0.584 Å pix$^{-1}$) were acquired during the first orbit, with a cumulative exposure time of 2311 seconds. Medium-dispersion spectra were acquired with the G140M grating (spectral resolution 0.053 Å pix$^{-1}$) during the remaining 4 orbits at central wavelengths of $\lambda_{1222}$ Å, $\lambda_{1272}$ Å, and $\lambda_{1567}$ Å covering the emission lines of Ly$\alpha$, N V, and C IV, respectively. The Ly$\alpha$ and C IV regions were observed for 1 orbit each, acquiring 2 spectra per orbit for cumulative exposure times of 2734 seconds each, and N V was observed for 2 orbits (4 spectra) for a cumulative exposure time of 5583 seconds.

The standard STSDAS$^1$ calstis pipeline was used to reduce the raw data to wavelength- and flux-calibrated 2D spectra. The nuclear spectra of Mrk 1044 were extracted from the linearized 2D spectra (STIS “x2d” science frames) using a 9 pixel (0.45 arcsec) aperture using the spectroid centroiding aperture-extraction task in XVista$^2$. Corresponding error spectra were also extracted from the STIS error arrays for each spectrum and co-added in quadrature and are dominated by photon noise. These 1D spectra form the basis of my subsequent analysis.

The G140L spectrum provides us with a reliable internal relative intensity calibration for the three non-overlapping G140M spectra, and provides information

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$^1$STSDAS is a product of the Space Telescope Science Institute, which is operated by AURA for NASA.

$^2$XVista is the current incarnation of Lick Observatory Vista, maintained in the public domain at http://ganymede.nmsu.edu/holtz/xvista.
on the overall UV spectral slope. The G140L spectrum with the flux-calibrated G140M spectra superimposed is shown in Figure 2.1. The individual flux-calibrated G140M spectra are shown in Figure 2.2.

2.3. Analysis

As can be seen in Figure 2.1, the UV spectrum of Mrk 1044 has a flat UV continuum with a slope of $\alpha = 0.0$ for $f_\nu \propto \nu^{-\alpha}$. Its emission line features are similar to those of many other AGN. Most prominent are the Ly$\alpha$, N V, and C IV emission lines. Less prominent, but certainly present are the Si II $\lambda$1265, O I $\lambda$1305, C II $\lambda$1335, Si IV $\lambda\lambda$1394,1403+O IV $\lambda$1402, N IV $\lambda$1486, He II $\lambda$1640, and O III $\lambda$1663 lines. Emission lines in general have a narrow ($< 1500$ km s$^{-1}$) component and a broad ($> 3000$ km s$^{-1}$) base. The presence of this base causes significant blending of Ly$\alpha$ and N V.

The three G140M spectra show a total of 24 possible absorption lines, all but four of which have good identifications. Line identification proceeded from three assumptions: 1) lines near the rest-frame wavelength of a well-known and strong transition are likely due to Galactic ISM, 2) any N V or C IV absorption line systems intrinsic to Mrk 1044 will also appear at the same velocity in Ly$\alpha$, and 3) any remaining unidentified absorption lines blueward of Mrk 1044’s Ly$\alpha$ emission line, but redward of 1216Å could be the signature of the low-redshift Ly$\alpha$ forest.
Line doublets of N V and C IV were identified by superposing velocity maps for each of the doublets. From the NASA/IPAC Extragalactic Database (NED), I adopt a systemic velocity of Mrk 1044 of 4932 km s$^{-1}$ ($z=0.01645$). Velocity maps are shown in Figure 2.3 for Ly$\alpha$, N V, and C IV. From these, I identify two intrinsic absorption systems at $-1145$ km s$^{-1}$ and $-295$ km s$^{-1}$. I find that the two candidate absorption systems in N V at $-2100$ km s$^{-1}$ and $+75$ km s$^{-1}$ are actually Galactic absorption from S II $\lambda\lambda 1251,1254$ in the case of the former and S II $\lambda 1260$ and an unknown absorption line superposed in velocity space in the case of the latter. In both cases, no corresponding absorption system is detected in C IV or in Ly$\alpha$.

I use two methods (each with slightly varying analysis paths) to measure the column densities of the absorbing material. The first is the standard curve of growth. More details of this process may be found in Spitzer (1978). To determine the velocity spread parameter, I calculate values of the column density for each line for 'b' values of 10, 20, 40, and 80 km s$^{-1}$. I then assume the velocity spread that gives the most consistent result between the line pair. The second method is the apparent optical depth method described by Savage & Sembach (1991). This method is usable with well-resolved lines and in such circumstances provides an independent method with which to estimate the column densities. A criterion for a line to be resolved is for the observed width to be sufficiently large that the width cannot be explained solely by the line-spread function of the instrument. I apply a conservative limit of $\Delta \lambda_{\text{obs}} \geq 2 \Delta \lambda_{\text{lsf}}$. I use the first-order line-spread function values for the 52X0.2
slit as given in the STIS Instrument Handbook for Cycle 13 of 1.45 pixels (G140L grating) and 1.66 pixels (G140M grating). Using the line widths (as gotten below) I conclude that in all cases are the absorption lines nominally resolved. In several cases the uncertainty in the line width indicates that the line is not definitively resolved (< 3σ above 2∆λ_{lsf}). These lines will be discussed in their appropriate sections below.

Lines in each of the spectra were first measured approximately with the analysis package LINER (Pogge & Owen 1993). Estimating the continuum is the single largest contributor to the systematic error budget of the absorption lines superposed over the emission lines. Because the emission lines cannot be easily modeled as geometrical objects (i.e. Gaussians) I performed nine by-eye spline fits to the continuum around each group of lines. All nine were done as reasonable fits, but several were purposefully fit to the outer envelope of the noise. To derive column densities via the curve of growth the resultant normalized (continuum=1) spectra and the best-fit absorption line parameters from the LINER package were used as input into the STSDAS analysis package SPECFIT (Kriss 1994). From this I receive the equivalent width, line centroid, and line width. The nine sets of these output parameters were then averaged to give the reported values. To determine the column densities via the apparent optical depth method the normalized residual flux (I_r) was taken directly from the LINER output spectra. Again, the nine resultant values were averaged to give the reported value.
The only variation in this analysis was with the G140L spectrum. Because of
the apparent flat continuum, the continuum was fit in LINER by a simple slope=0
line nine times. The determination of this line was still by eye. The analysis then
proceeded as above.

2.3.1. Mrk 1044 Emission Lines

Most of the metallicity studies of AGN have been restricted to using the
emission lines only. Therefore, I give measurements of my emission lines to place the
results of my absorption line study within the proper context. For each ion Table 2.2
gives the rest wavelength, the observed equivalent width, and the FWHM of the fit
components. For most emission lines I fit both a narrow and a broad component.
Both the N V and C IV emission lines exhibit an excess of red-ward flux which
I parameterized with an additional Gaussian. The Si IV+O IV] complex around
1400Å can be parameterized with several narrow components and one very broad
one, but these are so poorly constrained individually that I only report the gross
properties of the complex.

The literature contains many measures of AGN metallicity. Shemmer & Netzer
(2002)’s Figure 2 gives N V/C IV and N V/He II as a function of $\nu L_\nu$ at 1450Å.
Mrk 1044 has ratios of 0.6 and 3.1, respectively, at $1.3 \times 10^{12} L_\odot$. These values
place Mrk 1044 right in the middle of the NLS1 metallicity distributions, though
this object is slightly more luminous than the rest of the NLS1 sample considered by Shemmer & Netzer (2002). Nevertheless, Mrk 1044 remains at or above the mean metallicity-luminosity correlation. I can also place Mrk 1044 alongside the ultraviolet measurements of NLS1s in Wills et al. (2000). This object’s C IV/Lyα value of 0.59 is slightly higher than any of the NLS1s shown in their Figure 2. Mrk 1044’s (Si IV+O IV)/Lyα value of 0.17 is at the upper value bounded by their NLS1 sample. Finally, I can compare this object against the “nitrogen-rich” quasar Q0353-383 (Osmer 1980) and its recently discovered fraternity (Bentz & Osmer 2004). One of the metallicity indicator used in these studies is $f_{CIV}/(f_{Lyα} + f_{NV})$, of which Q0353-383 has the lowest value found to date: 0.07. By comparison, Mrk 1044 has a value of 0.45, a factor of six higher (lower metallicity). It should be noted that (Osmer 1980) found a value of $N/C = 10-20 \, (N/C)_\odot$, which is only a factor of three higher than the value I will discuss below in §2.4.

### 2.3.2. Mrk 1044 Absorption Line Systems

Of the 27 absorption lines found in my UV spectra, 10 of these appear to be intrinsic to Mrk 1044, organized into two distinct absorption systems. System 1 at $-1145 \, \text{km} \, \text{s}^{-1}$ contains strong lines of Lyα, N V, and C IV. System 2 at $-295 \, \text{km} \, \text{s}^{-1}$ contains strong lines of Lyα and C IV, and weak N V. Table 2.3 gives the measured and derived parameters for these systems: the observed wavelength, the observed equivalent width, the column densities, and the velocity offset from the systemic.
For those cases in which the line is not definitively resolved, I only give the column density derived from the curve of growth method. For those cases in which the line is most definitely resolved I give only the column density as derived from the apparent optical depth method. For those cases in which the line is well-resolved, but just so (only C IV \(\lambda 1549\) in Table 2.3), I give the results of both methods. Equivalent widths are typically around 0.2Å in the case of System 1 and 0.02Å in the case of System 2. The errors in the equivalent widths were determined by using estimates of the photon noise in each pixel. The errors in the velocity are set at 0.5 pixels, as given by the STIS Instrument Handbook for Cycle 13. Centroiding errors are much smaller and therefore ignored.

As can be seen from Table 2.3, neither System 1’s C IV \(\lambda 1551\) line, nor any of System 2’s lines are definitively resolved. Again, I consider a line definitively resolved if its observed width is \(> 3\sigma\) above \(2\Delta \lambda_{lsf}\). For the G140M grating, \(2\Delta \lambda_{lsf}\) varies between \(\sim 44\) km s\(^{-1}\) at 1200Å and \(\sim 33\) km s\(^{-1}\) at 1575Å. Between these two systems, it is not unexpected that none of System 2’s lines would pass this test given the more marginal nature of that system.

I calculate the degree of saturation of these two systems by measuring the ratios of the equivalent widths of each line doublet. Both N V and C IV have natural ratios of 2.0. This can be used to derive a covering fraction \((C_f)\) for each system following Hamann et al. (1997). System 1 has a consistent value of \(C_f = 0.80\) determined from both the N V and C IV lines. System 2 has less consistent values with \(C_f\) of
0.97 (N V) and 0.94 (C IV), but this is not unexpected given the more marginal nature of System 2’s N V doublet, the λ1243Å line of which I only detect at about the 2.5σ level. The covering fraction was taken into account while estimating the column densities from the equivalent widths.

I calculate N V/C IV column ratios for Systems 1 and 2. I use the weighted mean for each species from each doublet. In System 1, I find the N V/C IV ratio to be 2.5(±6%). For System 2 the ratio is 0.9(±20%).

2.3.3. Galactic Absorption Lines

With good certainty, I detect absorption lines of N I, Lyα, Si II, Si III, S II, and C IV in my medium-resolution spectra and Lyα, O I, C II, and Si II in my low-resolution spectrum from the ISM of our galaxy. To determine the velocity spread parameter $b$ for the curve of growth method, I look for the most consistent result between lines of the same species. Species for which I have only a single identified line I report a range of densities corresponding to a range of $b$ of 20-80 km s$^{-1}$. I give the results in Table 2.4 in the form of observed wavelength, likely identification, the candidate’s rest wavelength, the velocity width, the observed equivalent width, the derived column densities, and the relative velocity. As in Table 2.3, I give apparent optical depth column densities for the well-resolved lines, curve of growth column densities for the not well-resolved lines, and column densities
from both methods for those lines that are just above my resolution threshold. The velocities of the absorption components are scattered about zero and, in 12 of 14 cases, within three standard deviations of zero. It should be noted that there are systematic velocity shifts with respect to the parent spectrum. Two of the G140M spectra (Ly$\alpha$ and C IV) have all their Galactic absorption lines shifted to the blue, while the other G140M spectrum (N V) and the G140L spectrum have their Galactic absorption lines shifted to the red. This can also be seen, though not as clearly, in the lines given in Table 2.3. These shifts are not statistically significant if one accepts the absolute wavelength calibration error of 0.5 pixels. The errors in the equivalent widths are estimated from the photon noise.

Most of the FWHMs of the lines in the medium-resolution spectra sit between 50 and 70 km s$^{-1}$ with a few lines $\gtrsim 100$ km s$^{-1}$ (the Si lines and C IV $\lambda 1548$). The uncertainty in the width is not taken from any SPECFIT fit (which claims a formal precision on the order of one-tenth to one percent error on any one measurement) but instead from the scatter around the mean width measurement over many continuum fittings. This uncertainty is approximately 5 km s$^{-1}$ for almost all lines. The S II triplet lines have the best agreement amongst themselves, all coming within one standard deviation of their mean width, 61 km s$^{-1}$. The N I lines have a mean width of 70 km s$^{-1}$ and agree to within one standard deviation. The Si lines have a mean width of 126 km s$^{-1}$ and agree to within one standard deviation. The only real disagreement is from the C IV lines which disagree at greater than three standard
deviations. Of the galactic absorption lines, the three that are not definitively resolved are N I λ1201, Si II λ1527, and C IV λ1551.

The Galactic C IV lines suffer from another problem. The velocities (i.e. centroids) of these lines are in great disagreement with each other. The uncertainty in the velocity given is that induced by the absolute wavelength calibration. Wavelengths relative to one another in the same spectrum have their uncertainties smaller by a factor of 2.5 to 5. This creates a disagreement in the centroids of the C IV lines of more than 6σ. In addition, as can be seen from visual inspection of the spectrum (Figure 2.2), the profiles of these lines are dissimilar. It is possible that weak absorption from High Velocity Clouds (HVCs) is preferentially altering the shape of the stronger C IV λ1548 line. This could also explain the large differences in the FWHM of these lines. This hypothesis, however, cannot be tested with the current data and must wait for FUSE confirmations of the existence of HVCs through the detection (or not) of O VI.

The three absorption lines in the G140L spectrum (O I, C II, and Si II λ1527) have large widths of 883, 560, and 380 km s\(^{-1}\), respectively. All are fully resolved. It is possible that what I identify as simply O I could also be blended with S I λ1303. This would explain the large width and would eliminate O I’s large inferred velocity. Unfortunately, deblending does not return a clean result, so I cannot make this correction with any certainty and instead elect to omit it. The large values of inferred widths in the G140L spectrum is somewhat surprising, given that the low
ionization lines seen in the higher resolution spectra are all so narrow. The cause of this is not yet known and I caution against trusting the properties of these lines at this time.

The four unidentified absorption lines fail at least one of my criteria. To be identified, a line must come from a strong transition of an abundant element without having a sufficiently large velocity difference. For example, Si IIλ1264.7Å could be identified with the line at 1263.5Å but for the fact that this would give it a relative velocity of $-286$ km s$^{-1}$. I also use additional information such as the fact that the line in question has a width of 52 km s$^{-1}$ which makes it unlikely to come from Si whose lines average 123 km s$^{-1}$. It is possible that the absorption lines near the Ly$\alpha$ emission line of Mrk 1044 are Ly$\alpha$ whose systems simply do not have the column to appear in N V or C IV.

2.3.4. **INTERVENING Ly$\alpha$ ABSORPTION?**

The two unidentified absorption lines blueward of the Ly$\alpha$ emission line have velocities relative to Mrk 1044’s systemic velocity of about 2000 and 3000 km s$^{-1}$. While this does not particularly favor an origin as material intrinsic to Mrk 1044, it is not inconsistent with that hypothesis. If these absorption lines are due to intrinsic Ly$\alpha$, the inferred column densities are intermediate between Systems 1 and 2. Unlike those two systems, however, these unidentified systems do not show absorption in
either N V or C IV. An alternative hypothesis is that these two systems are due to the low-redshift Lyα-forest. To test this, I calculate the number of expected absorption systems from the results of Penton et al. (2004). They parameterize the number of systems per unit log column density and per unit redshift \( \frac{\partial^2 N}{\partial N_{HI} \partial z} \) as \( C_{HI} N^{-\beta}_{HI} \) with \( C_{HI} = 10^{10.3} \) and \( \beta = 1.65 \) between \( \log N_{HI} \) of 12.3 and 14.5. For my observed spectra, I calculate the 3σ detection limit of Lyα absorption to be \( \log N_{HI} = 12.77 \). Because this is almost a factor of ten lower in column density than the weaker of my systems, I reanalyze the spectrum for weak lines. My best continuum fit (flattest continuum-divided spectrum) can be seen in Figure 2.4. While any one continuum fit may produce several well-detected line candidates, I require any line to be well-detected in the majority of my nine continuum fits. Only one additional line passes this test, being detected, on average, at exactly 3σ. The wavelengths, velocity widths, equivalent widths, calculated column densities and relative velocities of the two strong Lyα systems and the weak, newly found system are given in Table 2.5. For the decade above my detection limit, and for a path length \( \Delta z = z_{\text{Mrk}1044} = 0.01645 \), 2.0 systems are expected, and two systems (within my column density uncertainties) are detected. The expected number of systems at all higher column densities (\( \log N_{HI} > 13.77 \)) and the same path length is 0.6 and I detect one. In this manner, the attribution of these absorption lines to intergalactic Lyα absorption is perfectly reasonable.
2.4. Discussion

The N V/C IV ratio does not tell us the N/C abundance ratio until I apply an ionization correction for each species. This ionization correction is the greatest source of systematic uncertainty in the determination of abundances. An accurate ionization correction requires measurements of multiple species of a single element, and preferably as many additional elements as possible. For this reason, I cannot create an accurate ionization model with just this HST data. I am able, however, to set a lower limit on the N/C abundance ratio by calculating the N V/C IV ratio in a region with physical parameters optimized such that the maximum amount of N is in N V (see Hamann & Ferland 1999). This lower limit is not unique but varies according to the input photoionization spectrum. I invert the equation

\[
\frac{N\ 	ext{V}}{C\ 	ext{IV}} = \frac{A(N)}{A(C)} \times \frac{(N\ 	ext{V}/N)}{(C\ 	ext{IV}/C)}
\]

where \(A(N)/A(C)\) is the total Nitrogen to total Carbon abundance ratio (henceforth N/C), the quantity I wish to measure. Following Hamann & Ferland (1999) (their Figure 10), I find that N V has a maximum ionization fraction of 0.37 at \(\log U\) of \(-1.54\). The fraction of Carbon in C IV at the same ionization parameter is 0.18. Using my observed ratio of N V/C IV=2.5 from System 1, this gives a minimum N/C ratio of 1.2, or \(3.9\ (N/C)_\odot\) \((\pm 6\%)\). Doing the same analysis with the weaker absorption lines of System 2 gives a minimum N/C ratio of only \(1.4\ (N/C)_\odot\) \((\pm 20\%)\).
The errors quoted only incorporate uncertainties due to measurements derived from the spectra.

To demonstrate the discrepancies caused by improper ionization corrections, I compute the minimum N/C for an alternative model. I do this by running the photoionization-equilibrium code Cloudy 94\(^3\) (Ferland et al. 1998) with a differing spectral energy distribution (SED) (Cloudy’s standard AGN SED) from that used in Hamann & Ferland (1999) (a power law SED with \(\alpha = -1.5\) and a near-infrared break around 1-2 \(\mu\)m). In this case, I find that System 1 has a lower limit on its abundance ratio at 2.6 \((N/C)_{\odot}\). This can be compared with the value of 3.9 using Hamann & Ferland (1999) as above. The estimated error due to photon noise is only \(~6\%)\, which demonstrates that my result is dominated by systematic uncertainty in the ionization corrections, and more accurate results await data at other wavebands that should permit calculation of a detailed photoionization model for these spectra. Until such a model is constructed, I am limited to stating only that Mrk 1044 has line strengths consistent with a super-solar N/C ratio.

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\(^{3}\)Cloudy version C94.00, obtained from the Cloudy webpage http://www.nublado.org/
Fig. 2.1.— The three G140M spectra superposed over the G140L spectrum. Emission lines are marked above the spectrum, absorption below.
Fig. 2.2. — The three G140M spectra each shown separately. Intrinsic absorption systems are marked above the lines, Galactic lines are marked below.
Fig. 2.3.— Velocity maps around Systems 1 (left) and 2 (right). In the case of C IV and N V, the dotted lines signify the shorter wavelength line of the pair, while the solid lines signify the longer wavelength line. System 1 is very secure with all three ions showing absorption at that velocity. System 2 is less obvious with the N V lines showing little contrast. Also visible at $\sim +75\,\text{km}\,\text{s}^{-1}$ is the chance alignment of a Galactic S II line with a yet unidentified line. Evidence against this candidate being a true system is the lack of corroborating absorption at that velocity in C IV and Ly$\alpha$. 
The normalized (continuum divided) spectrum blueward of the Ly$\alpha$ emission line of Mrk 1044. This is one of nine by-eye spline fits to the local continuum (i.e. the Ly$\alpha$ emission line) as described in §2.3. The absorption feature at 1228.3Å is a 3σ detection. Other possible absorption features such as those blueward of 1224Å or at 1233.5Å have significant detections in only some of the nine continuum fits.
### Table 2.1. Journal of Observations.

<table>
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<tr>
<th>Grating</th>
<th>Central Wavelength [Å]</th>
<th>Spectral Resolution [Å pix(^{-1})]</th>
<th>UTC Date (start)</th>
<th>Exposure Times [s]</th>
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<td>G140L</td>
<td>1425</td>
<td>0.584</td>
<td>2003-06-28T04:46:49</td>
<td>1200 &amp; 1011</td>
</tr>
<tr>
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<td>0.053</td>
<td>2003-06-28T06:14:08</td>
<td>1294 &amp; 1440</td>
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<tr>
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<td>1222</td>
<td>0.053</td>
<td>2003-06-28T07:50:11</td>
<td>1294 &amp; 1440</td>
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<tr>
<td></td>
<td>1272</td>
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<td>1294, 1409 &amp; 2×1440</td>
</tr>
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<td>Ion</td>
<td>$\lambda_{\text{Rest}}$ [Å]</td>
<td>Equivalent Width [Å]</td>
<td>FWHM-Narrow [km s$^{-1}$]</td>
<td>FWHM-Broad [km s$^{-1}$]</td>
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<td>-------------</td>
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<td>-----------------------</td>
<td>---------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>H I</td>
<td>1216</td>
<td>113.6 ± 0.1</td>
<td>1120.6 ± 0.3</td>
<td>3406 ± 3</td>
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<tr>
<td>N V</td>
<td>1239, 1243</td>
<td>40.2 ± 0.4</td>
<td>1070 ± 40</td>
<td>5530 ± 50$^a$</td>
</tr>
<tr>
<td>O I</td>
<td>1302</td>
<td>4.9 ± 0.7</td>
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<td>3600 ± 200</td>
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<tr>
<td>C II</td>
<td>1336</td>
<td>2.94 ± 0.04</td>
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<td>Si IV+O IV]</td>
<td>1394, 1403+1402</td>
<td>19.19 ± 0.03</td>
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<td>~ 10000</td>
</tr>
<tr>
<td>N IV]</td>
<td>1486</td>
<td>0.984 ± 0.005</td>
<td>1262 ± 4</td>
<td>⋯</td>
</tr>
<tr>
<td>C IV</td>
<td>1548, 1551</td>
<td>67.0 ± 0.3</td>
<td>1317 ± 3</td>
<td>3400 ± 30$^b$</td>
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<tr>
<td>He II</td>
<td>1640</td>
<td>12.9 ± 0.5</td>
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<td>7500 ± 200</td>
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<tr>
<td>O III]</td>
<td>1663</td>
<td>5.2 ± 0.4</td>
<td>⋯</td>
<td>3400 ± 200</td>
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$^a$Line asymmetry requires a third (red) Gaussian with FWHM= 3450 ± 20 km s$^{-1}$

$^b$Line asymmetry requires a third (red) Gaussian with FWHM= 7320 ± 30 km s$^{-1}$

Table 2.2. Emission Lines.
<table>
<thead>
<tr>
<th>Line</th>
<th>Wavelength [Å]</th>
<th>FWHM [km s⁻¹]</th>
<th>Equivalent Width [mA]</th>
<th>log(Column) [cm⁻²]ᵃ</th>
<th>log(Column) [cm⁻²]ᵇ</th>
<th>Velocity [km s⁻¹]</th>
</tr>
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<tr>
<td>System 1</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Lyα</td>
<td>1230.9819</td>
<td>92 ± 7</td>
<td>341 ± 5</td>
<td>14.11 ±0.04</td>
<td>14.11 ±0.04</td>
<td>-1156 ± 7</td>
</tr>
<tr>
<td>N V1239</td>
<td>1254.4633</td>
<td>71 ± 3</td>
<td>209 ± 8</td>
<td>14.33 ±0.03</td>
<td>14.33 ±0.03</td>
<td>-1143 ± 6</td>
</tr>
<tr>
<td>N V1243</td>
<td>1258.4999</td>
<td>71 ± 3</td>
<td>162 ± 6</td>
<td>14.45 ±0.02</td>
<td>14.45 ±0.02</td>
<td>-1143 ± 6</td>
</tr>
<tr>
<td>C IV1549</td>
<td>1567.7329</td>
<td>50 ± 6</td>
<td>204 ± 5</td>
<td>13.94 ±0.02</td>
<td>13.94 ±0.02</td>
<td>-1147 ± 5</td>
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<tr>
<td>C IV1551</td>
<td>1570.3602</td>
<td>47 ± 5</td>
<td>156 ± 4</td>
<td>14.04 ±0.02</td>
<td>14.04 ±0.02</td>
<td>-1143 ± 5</td>
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<tr>
<td>System 2</td>
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<td></td>
</tr>
<tr>
<td>Lyα</td>
<td>1234.4395</td>
<td>50 ± 8</td>
<td>16 ± 3</td>
<td>12.48 ±0.07</td>
<td>12.48 ±0.07</td>
<td>-303 ± 6</td>
</tr>
<tr>
<td>N V1239</td>
<td>1257.9923</td>
<td>90 ± 20</td>
<td>23 ± 5</td>
<td>13.07 ±0.09</td>
<td>13.07 ±0.09</td>
<td>-290 ± 6</td>
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<tr>
<td>N V1243</td>
<td>1262.0425</td>
<td>100 ± 50</td>
<td>10 ± 4</td>
<td>13.00 ±0.15</td>
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<td>-289 ± 6</td>
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<tr>
<td>C IV1548</td>
<td>1572.1322</td>
<td>43 ± 10</td>
<td>42 ± 4</td>
<td>13.03 ±0.04</td>
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<td>C IV1551</td>
<td>1574.7397</td>
<td>38 ± 10</td>
<td>29 ± 2</td>
<td>13.16 ±0.03</td>
<td>13.16 ±0.03</td>
<td>-296 ± 5</td>
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ᵃDerived from curve of growth arguments
ᵇDerived from optical depth integration

Table 2.3. Measured Absorption Lines and Calculated Column Densities in Mrk 1044.
<table>
<thead>
<tr>
<th>$\lambda_{\text{Obs}}$ [Å]</th>
<th>Ion</th>
<th>$\lambda_{\text{Rest}}$ [Å]</th>
<th>FWHM Width [mÅ]</th>
<th>Equivalent log(Column) $[cm^{-2}]^a$</th>
<th>log(Column) $[cm^{-2}]^b$</th>
<th>Velocity [km s$^{-1}$]</th>
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<tbody>
<tr>
<td>1199.5251</td>
<td>N I</td>
<td>1199.550</td>
<td>76 ± 7</td>
<td>210 ± 10</td>
<td>$14.50^{+0.46}_{-0.34}$</td>
<td>$14.25^{+0.06}_{-0.07}$</td>
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<tr>
<td>1200.1924</td>
<td>N I</td>
<td>1200.223</td>
<td>65 ± 5</td>
<td>160 ± 10</td>
<td>$14.41^{+0.36}_{-0.35}$</td>
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<tr>
<td>1200.6842</td>
<td>N I</td>
<td>1200.710</td>
<td>90 ± 20</td>
<td>170 ± 10</td>
<td>$14.76^{+0.40}_{-0.36}$</td>
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<tr>
<td>1206.4296</td>
<td>Si III</td>
<td>1206.500</td>
<td>140 ± 10</td>
<td>500 ± 20</td>
<td>$13.63^{+0.03}_{-0.03}$</td>
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<tr>
<td>1250.6094</td>
<td>S II</td>
<td>1250.584</td>
<td>60 ± 6</td>
<td>93 ± 8</td>
<td>$15.15^{+0.04}_{-0.04}$</td>
<td>$15.18^{+0.05}_{-0.05}$</td>
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<tr>
<td>1253.8245</td>
<td>S II</td>
<td>1253.811</td>
<td>60 ± 5</td>
<td>129 ± 7</td>
<td>$15.05^{+0.03}_{-0.03}$</td>
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<td>1259.5310</td>
<td>S II</td>
<td>1259.519</td>
<td>64 ± 5</td>
<td>169 ± 5</td>
<td>$15.10^{+0.02}_{-0.02}$</td>
<td>$15.13^{+0.02}_{-0.03}$</td>
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<td>1260.4310</td>
<td>Si II</td>
<td>1260.422</td>
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<td>498 ± 8</td>
<td>$13.24^{+0.02}_{-0.02}$</td>
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<tr>
<td>1303.0942$^c$</td>
<td>O I</td>
<td>1302.168</td>
<td>883 ± 7</td>
<td>553 ± 5</td>
<td>$14.80^{+0.08}_{-0.09}$</td>
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<tr>
<td>1334.9145$^c$</td>
<td>C II</td>
<td>1334.532</td>
<td>560 ± 10</td>
<td>720 ± 30</td>
<td>$14.18^{+0.21}_{-0.42}$</td>
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<tr>
<td>1527.0709$^c$</td>
<td>Si II</td>
<td>1526.707</td>
<td>380 ± 60</td>
<td>280 ± 50</td>
<td>14.09-14.50</td>
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<td>1548.1517</td>
<td>C IV</td>
<td>1548.187</td>
<td>97 ± 8</td>
<td>240 ± 20</td>
<td>$13.79^{+0.09}_{-0.11}$</td>
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<tr>
<td>1550.6375</td>
<td>C IV</td>
<td>1550.772</td>
<td>50 ± 10</td>
<td>120 ± 20</td>
<td>$13.80^{+0.05}_{-0.06}$</td>
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$^a$Derived from curve of growth arguments

$^b$Derived from optical depth integration

$^c$From the low-resolution spectrum. Use with caution.

Table 2.4. Galactic and Unidentified Absorption Lines.
<table>
<thead>
<tr>
<th>$\lambda_{\text{Obs}}$ [Å]</th>
<th>FWHM [km s$^{-1}$]</th>
<th>Equivalent Width [mÅ]</th>
<th>log(Column) [$cm^{-2}$]$^a$</th>
<th>log(Column) [$cm^{-2}$]$^b$</th>
<th>Velocity: Rest Frame [km s$^{-1}$]</th>
<th>Velocity: Mrk 1044 [km s$^{-1}$]</th>
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<tr>
<td>1224.3067</td>
<td>88 ± 4</td>
<td>251 ± 9</td>
<td>13.80$^{+0.02}_{-0.03}$</td>
<td>2130 ± 7</td>
<td>−2801 ± 7</td>
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<tr>
<td>1227.6204</td>
<td>120 ± 10</td>
<td>175 ± 7</td>
<td>13.56$^{+0.05}_{-0.06}$</td>
<td>2937 ± 7</td>
<td>−1994 ± 7</td>
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<tr>
<td>1228.3089</td>
<td>70 ± 20</td>
<td>45 ± 15</td>
<td>12.96$^{+0.14}_{-0.19}$</td>
<td>3117 ± 7</td>
<td>−1814 ± 7</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Derived from curve of growth arguments

$^b$Derived from optical depth integration

Table 2.5. Likely Ly$\alpha$ Forest Lines.
Chapter 3

FUSE Observations of Markarian 1044

3.1. Introduction

I could not perfectly determine the photoionization correction for the outflowing gas in Mrk 1044 using only data from HST. This problem is common in studies that cover only a small wavelength range and/or contain information on few or one species of a particular element. For this reason I extend the baseline of observed species in Mrk 1044 by adding measurements of O VI observed by the Far Ultraviolet Spectroscopic Explorer (FUSE) to the previous measurements detailed in chapter 2. This data is at approximately the same epoch allowing us to ignore systematic problems such as the passage of clouds across the line of sight that would otherwise plague combined-data-set studies. Neither data set alone can break the degeneracies in making the photoionization correction, but both data sets together select a small region of parameter space from which I can determine the bulk metallicity and the abundance mixture.
3.2. Observations and Data Reduction

Mrk1044 was observed by the FUSE satellite on UTC 2004 January 01 and 02. The observation was conducted over one ~ 7 hour series of exposures from MJD 53005.74609375 to 53006.046875. The data sets are D0410101. The received data were reduced by the standard CalFUSE pipeline (2.4.1). The FUSE IDL tool FUSE_REGISTER was used to cross-correlate, weigh, and coadd the spectra. I use the observations with the 1A detector segment and the LiF mirror (987 Å–1082 Å) in this analysis as it contains the data I wish to analyze and is the least noisy of the eight FUSE detector segments. To achieve the necessary S/N, the LiF 1A spectrum is binned by a factor of 10. The resultant spectrum has a pixel size of ~ 20 km s\(^{-1}\) (the FWHM of the instrument) and S/N ratios 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 3.1. 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 Å to 1180 Å. The source has two emission

\^See http://fuse.pha.jhu.edu/analysis/calfuse.html
line complexes, the most obvious being the blend of Ly$\beta$ and O VI $\lambda$1032,1038 Å observed from 1030 Å to 1060 Å. The other, much weaker, is N III $\lambda$990,992 Å 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 Mrk1044.

Before the data can be analyzed for absorption systems of any sort, the pseudo-continuum (continuum + emission lines) must be modeled. The emission lines were first fit using standard Gaussians. The discussion of the line properties will be reserved to its own section (§3.3.2). This technique failed, however, to fit the profile of the emission lines so as to result in a well-modeled pseudo-continuum. Because the profile of the emission lines was sufficiently non-Gaussian, I instead fitted, by eye, a spline to the emission line structure and used this to normalize the spectrum (divided through such that the resultant spectrum nominally varies between zero and one).

3.3. Analysis

I 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 will give us additional insight into whether these lines give trustworthy results. Even though studies such as Arav et al. (2005) have found that some absorption features result from inhomogeneous systems, I feel confident in the utility of these methods. The reason for my trust can be found in the HST spectra of Mrk 1044. In the (Fields et al. 2005a, henceforth F05; see also Chapter 2) study, one can see two distinct absorption systems. System 1 at $-1158\ \text{km s}^{-1}$ and System 2 at $-286\ \text{km s}^{-1}$. 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 I am dealing with a kinematically simple system (a single absorber). The analysis of lines in my FUSE spectrum associated with System 1 should then be unaffected by possible inhomogeneities. System 2, however, exhibits weak lines, has much more noise in its profile, and as a consequence I do not have the data to make the same argument in favor of a single absorber. My analysis in §3.3.3 is focused upon lines associated with System 1 and I touch but briefly upon lines of System 2 so I do not anticipate that my conclusions will be adversely affected.

The spectra were normalized in the analysis package LINER (Pogge & Owen 1993), a standalone software tool for the analysis of astronomical spectra. I also used LINER to derive initial estimates of the properties of the emission and absorption lines. The resultant 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. I calculated the column density for velocity spread parameter $b$-values of 10, 20, 40, and 80 km s$^{-1}$, but I 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 the absolute velocities should be shifted positively by about 3–5 km s$^{-1}$, while the FUSE White Paper on the subject shows that the relative wavelength errors where my lines are located are about 8 km s$^{-1}$. I adopt this value as the uncertainty in my centroiding.

To determine if the Apparent Optical Depth method is appropriate, the first test is whether a line is resolved ($\Delta \lambda_{obs} \geq 2 \Delta \lambda_{lsf}$). I compared FUSE’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 three standard deviations above the nominal resolution limit. If a line passes these tests, I use the
normalized residual flux \( (I_r) \) that results from the LINER pseudo-continuum fit and integrate over the line.

I have determined two major sources of uncertainty in my line parameters. The first is the standard photon noise one expects which can be propagated through each stage of the analysis process. The second is uncertainty associated with a sub-optimal fit to the pseudo-continuum. I 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. I 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 my uncertainty. In all cases, the fit to the pseudo-continuum 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.

3.3.1. 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 ($H_2$). I use the template of Romano et al. (2002) to model the $H_2$ absorption lines.

The identification of the Galactic metal absorption lines in my spectrum followed from Sembach (1999). For the physical properties of the metal lines I used the NIST Atomic Spectra Database\(^2\) as well as the compilation of Morton (2003). The metal lines found are $C\quad II\quad \lambda\lambda1036,1037\;\AA$, $O\quad I\quad \lambda1039\;\AA$, $Ar\quad I\quad \lambda1048\;\AA$, and $Fe\quad II\quad \lambda\lambda1055,1063\;\AA$. The expected $O\quad VI\quad \lambda\lambda1032,1038\;\AA$ 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 cores 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

\(^2\)http://physics.nist.gov/PhysRefData/
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 multi-pixel 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, I rebin the data by only a factor of 3 (instead of 10), giving us a spectrum with approximately three pixels per resolution element. This does not suggest a multi-component ISM within the bounds of my noise. Because of these problems, I 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 II* at 1036 and 1037 Å and the Ly$\beta$ line of the stronger system in Mrk 1044 (discussed later in §3.3.3). Ultimately, I chose to fit to the isolated weak H$_2$ lines, like those around 1041 Å 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 my 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 FUSE LiF 1A spectrum are listed in Table 3.1. 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). I 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 II* especially, and the
fit was unstable in SPECFIT. These lines are characterized by poor determinations of their physical parameters. For example, the centroid velocity of C II* is very inconsistent with zero indicating that the deblending was unsatisfactory. Because of the deblending problem, I do not provide column density measurements for either of the C II lines. I do provide the measurements of the physical parameters (EW, FWHM, $v_{\text{rel}}$) in the table along with their large uncertainties to illustrate the extent of the effects of the deblending. The redward Fe II line ($\lambda$1063 Å) is blended in its wings with H$_2$ which impairs my ability to successfully match line parameters. Regardless, the two Fe II lines match well in velocity and column density, matching best at a $b$ value of 20 km s$^{-1}$, 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$\sigma$ level, due primarily to the uncertain deblending of the redward line. The O I line appears to be definitively resolved, so I give its column density via the apparent optical depth method. If I choose the same $b$ parameter as matches best between the Fe II lines, I 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 I$\lambda$1302 Å as found in F05 has contradictory parameters. As mentioned in that study, O I$\lambda$1302 Å 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 I, Ar I & both Fe II) have a
velocity consistent with zero, while the two C II lines have the most discrepant velocities and are also the lines most heavily blended with H₂.

### 3.3.2. Mrk 1044 Emission Lines

While this paper is primarily focused upon the absorption line results, I 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 3.2. Given for each line (Lyβ, N III and O VI) are the equivalent widths, the Gaussian FWHM for any components they have, and the velocity offset from systemic (4932 km s⁻¹). I 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 will be given relative to this velocity. In general, the emission lines are offset by hundreds of km s⁻¹ blueward, though there does not appear to be a consistent velocity offset among the emission lines. The N III doublet is weak enough so as to be fit with a single Gaussian each, while the O VI doublet requires a narrow and broad component each. The Lyβ 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 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. I 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\(\beta\) and because it is blended with O 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 VI complex (2 narrow, 2 broad) always leaves an excess of blueward flux, 2) a six-component fit (3 per O VI) is not sufficiently superior to a broad Ly\(\beta\) + four-component O VI and 3) the centroid of the component blueward of the O VI is generally consistent with the redshift of the other emission lines (Ly\(\beta\), N III).

3.3.3. Mrk 1044 Absorption Line Systems

With the pseudo-continuum normalized and the Galactic lines identified, I constructed velocity maps each associated with a particular atomic transition and shifted to the systemic velocity of Mrk 1044. These velocity maps, my Figure 3.2, cover the same ranges shown in Figure 3 in F05. My figure shows the likely counterparts to the absorbing systems found by F05 for Ly\(\alpha\), N V and C IV: the strong System 1 at \(-1158\) km s\(^{-1}\) and the weaker System 2 at \(-286\) km s\(^{-1}\). Figure 3.2 also illustrates the danger of not fully identifying Galactic lines before doing a velocity study: the feature at \(-200\) km s\(^{-1}\) appears to be an absorbing system in
all but N\textsc{iii} \(\lambda 990\) Å. However, what could be the O\textsc{vi} \(\lambda 1032\) Å line at \(z=0.01578\) is actually Ar\textsc{i} \(\lambda 1048\) Å at \(z=0.0\). Another way in which Galactic absorption affects my 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 System 1 or 2, and no Ly\(\beta\) is found at System 2. I note that there appears to be an absorption system at \(v \approx 0\) 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 I cannot extract reliable information about this unconfirmed absorption system due to the scarcity of its absorption lines, I do not consider it further.

I report good (> 3\(\sigma\)) detections of four lines belonging to absorption systems intrinsic to Mrk\,1044. I find a velocity for System 1 of –1158 km s\(^{-1}\) and a velocity for System 2 of –286 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 \(3.3\) 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) I give only the column
density derived from the curve of growth method. For System 1 I also give the
apparent optical depth column density, though it should be noted that only the
O VI lines are definitively resolved (> 3σ above the 2Δλ_{lsf} limit which is about
40 km s\(^{-1}\)). Additionally, the 3σ upper limits on the undetected N \textsc{iii} lines are given.

To determine the column densities with the apparent optical depth method,
I 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} λ1038 Å (I\(_1\) in their
formalism) has a smaller normalized flux value in its trough than O \textsc{vi} λ1032 Å (I\(_2\)),
on average about 0.10 to 0.15, respectively. This is illustrated in Figure 3.3. This is
unphysical, and I attempted to solve this problem by modifying the lines as follows.
I note that the uncertainties on data points in the absorption troughs of these lines
are about 0.05, and so I calculate two covering fractions, one where the trough of I\(_2\)
was decreased by 1σ, and one where the trough of I\(_1\) was increased by 1σ. 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, still failed for the majority
of my pseudo-continuum normalizations. The second method (increasing I\(_1\)) mostly
succeeded (the O \textsc{vi} λ1032 Å \(C_f + I_{\text{trough}} = 1\) in two of the nine normalizations) so
I used this method to determine my covering fraction. I set my integration limits
where the flux clearly deviated from the continuum. Figure 3.3 illustrates this
happening between velocities of \(~ -1110\) km s\(^{-1}\) 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 I 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, I 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), I do not consider this discrepancy in covering fraction a problem to be corrected.

There is one major caveat that must be addressed with regards to the measurement of the Ly$\beta$ line of System 1, namely that this line is heavily blended with a Galactic H$_2$ line. This is demonstrated by Figure 3.4 which shows the nine pseudo-continuum fits, before and after the H$_2$ 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 my Lyβ measurements compared to the other absorption lines. What isn’t reflected in these uncertainties is systematic effects, such as a blueshift in the Lyβ line by about three times the wavelength uncertainties. Compared to the Lyα-derived H I column densities from F05, the Lyβ-derived value is a factor of 2–4 larger. If the Lyα value is correct, the H2 line blended with Lyβ are likely under-subtracted. In this case, my Lyβ derived value should represent an upper limit on the total H I column. However, increasing the strength of the H2 line shifts the Lyβ line to an even more discrepant centroid. The disagreement between these two Lyman lines could be resolved by observation of higher-order Lyman series lines, such as Lyγ, 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 Lyγ, the entire “line” is only a 1σ or 1.5σ detection. With no guidance from other Lyman series lines, I must instead assess which line, Lyα or Lyβ, is more trustworthy. As Figure 4 of F05 shows, the Lyα 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 3.4 shows a very asymmetric Lyβ line and the normalization is not nearly as well determined. I therefore adopt the Lyα line as the measure of the H I column density. Even so, I also wish to point
out that if the Ly$\beta$ line is taken as the fiducial line, this changes my results only in magnitude, not in quality, as I will see in §3.4.

To determine the elemental column densities from the ionic column densities, I must make an ionization correction. To do so, I used the photoionization-equilibrium code Cloudy. This code creates a model of gas in equilibrium with a photoionizing flux. From this, I 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) $N_H$, the column density of hydrogen through the cloud. My analysis method was to select a limited set of metallicity and SEDs, over which I then varied $U$ and $N_H$ to create a series of two-dimensional simulation grids. My analysis was primarily based upon Cloudy’s standard AGN template SED and a metallicity of solar in abundance and mixture. The grid of log $U$ and log $N_H$ input values ranged for log $U$ from $-2$ to 0 and log $N_H$ from 18 to 20, respectively with spacing of 0.01. From this I extracted predicted column densities of relevant ions.

I 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 I will use are 
\[ \log_{10} C_{\text{IV}} = 14.47 \pm 0.06 \] and \[ \log_{10} N_{\text{V}} = 14.46 \pm 0.02. \] I compute the column density of 
\( \text{H I} \) 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 3.5. In this figure each 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 \( N_{\text{V}} \) column densities can 
be used to illustrate the interplay between \( \log U \) and \( \log N_H \). At constant \( \log N_H \) the 
total quantity of Nitrogen is fixed, but the fraction of Nitrogen in the form of \( N_{\text{V}} \) 
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 \( N_{\text{VI}}, N_{\text{VII}} \) and \( N_{\text{VIII}} \). For example, at \( \log N_H = 19 \), 
there are two possible physical conditions that produce the observed quantity of 
\( N_{\text{V}} \) column density. At smaller values of \( \log N_H \), there is less total Nitrogen, and 
eventually there is not enough Nitrogen to create the observed column of \( N_{\text{V}} \). 
This example also shows the necessity of observing multiple species. If I only had 
measurements of \( N_{\text{V}} \) and \( \log N_H \) was 19, I 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 my observations, but there is a small zone around \( \log U = -1.29, \log N_H = 18.85 \) 
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 I observe.

I also investigated how the choice of the incident continuum affects my 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 3.5, 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 $N_H$ by between 0.4 and 0.6 dex. I 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 to that due to SED differences between the Cloudy “table agn” and the two NLS1s. I also tested non-solar abundance mixtures by increasing Nitrogen by factors of 2 and 4. I find my data are consistent at the $3\sigma$ level with overabundant Nitrogen at twice the solar mixture, but inconsistent with four-times-solar.
3.3.4. Intergalactic Absorption

Following my analysis in F05, I searched my FUSE data for intergalactic absorption lines. In F05 three Lyα 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 Lyβ line would be about 40 mÅ. The 3σ detection in this region is around 100 mÅ, determined from the rms values of the data at the continuum and assuming a three-pixel-wide absorption line. Regardless, there are two absorption features that appear to be the Lyβ counterparts of the two stronger of the Lyα absorption systems. Lyβ associated with the weakest of the three Lyα systems is coincident with a blend of Galactic H₂ and C II lines and given the problems with deblending described in §3.3.1 make its recovery problematic. The other two Lyα systems should have corresponding absorption in Lyβ at 1033.0 Å and 1035.8 Å, and I find two systems at 1033.1 and 1035.7 Å with equivalent widths of 105 mÅ and 80 mÅ, respectively. By this measure, the weaker line is not definitively detected and the stronger is very close to the nominal 3σ limit. It should be noted that at the location of the stronger line the pseudo-continuum is at an apparent minimum, lying between the O VI emission line and some excess flux that rises towards the blue for about 5 Å (see Figure 3.1). 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 3σ 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\$ level (indeed consistent with zero at the 3\$ level). For this reason I suggest the Ly$\alpha$ determined values for this system stand as the measurement of these systems.

3.4. DISCUSSION

As discussed in §3.3.3, 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 $U = -1.29, \log N_H = 18.85$ with the standard Cloudy AGN SED) which 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. $\log N_H$ is actually 18.15), then all measured lines (assuming 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 five times solar (+0.7 dex), this is inconsistent with the assumption that N/O scales like O/H (Hamann
& Ferland 1999, and references therein), at least for this object. If Nitrogen did scale with metallicity, the N V curve in Figure 3.5 should lie as far above the C IV–O VI agreement point as the H I lies below it, which it clearly does not. The best-fit Nitrogen is at most 0.06 dex above such a point. At most, Nitrogen can be overabundant with respect to the solar mixture by a factor of 2, above which it shares no model in common with both Carbon and Oxygen. Understandably then, this paper gives a much higher value of Z than that found in F05 (minimum ~ 1.5 solar) where it was assumed that $N \propto Z^2$.

The effects of the assumed SED on the metallicity can be large. As mentioned in §3.3.3 the metal lines shift to more negative values of log $U$ when a NLS1-specific SED is used, the result of which is that the agreement point is near log $U = -1.7$. The major change, however, is the shift of H I to smaller values of log $N_H$ which increases the inferred value of the metallicity by another factor of 2–4 (to between 10 and 20 times solar) with the SED of NGC 4051 providing the highest metallicity. To confirm these extremely high values of the metallicity I reran Cloudy with the metals set to 5 or 10 times the solar value for the standard and NLS1 SEDs respectively. To be fully self-consistent, I also took Helium enrichment into account. For one model of Helium enrichment ($\Delta Y/\Delta Z = 2$) and bulk metallicity around 10 times solar, log($He/H$) $\approx -0.52$. Including this effect does not change my 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, I find log $U = -1.20 \pm 0.04$, log $N_H = 18.13 \pm 0.02$ and $Z = 5_{-1}^{+2}$ solar metallicities. For the Ark 564 SEDs I find log $U = -1.55 \pm 0.03$, log $N_H = 17.86 \pm 0.02$ and $Z = 17_{-3}^{+5}$. For the NGC 4051 SED I find log $U = -1.68 \pm 0.03$, log $N_H = 17.85 \pm 0.02$ and $Z = 22_{-4}^{+7}$. 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 [3.6]. The $\chi^2$ surface for the standard AGN SED with five times solar metallicity (and no shift in H I) is shown in Figure [3.7]. Lines of constant $\chi^2$ are projected into the log $U$–log $N_H$ plane. The smoothness and parabolic shape of the $\chi^2$ surface indicate that I have well-sampled the log $U$–log $N_H$ parameter space. I remind the reader that I have used a Ly$\alpha$-derived value of $N_{HI}$ that is much smaller than the Ly$\beta$-derived value. If I instead adopt the Ly$\beta$ value, the inferred bulk metallicity is $+0.3$ dex (twice solar) using the same arguments, though I have discussed why Ly$\beta$ should not be used in §3.3.3.

This study reinforces the necessity of having a wide range of ionic species to accurately model the physical conditions in these absorbing systems. If I had created the same models as I did in this study, but only using the F05 data and assuming $N \propto Z^2$, I 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 $N_H$ plane. While I 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 doublet is what allows us to determine a metallicity without the assumption of $N \propto Z^2$. I must therefore assess how my 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 I have actually measured a lower limit on the column density, or 2) that my value of the covering factor is too small, in which case the actual column density is likely smaller in magnitude than my 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 Figure 3.3) 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 VI$\lambda$1032 Å line. The uncertainty on the apparent-optical-depth-derived column density (see Table 3.3) 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 $+C_f \approx 1$ which is true near or at saturation. This saturation is likely not to be heavy, however, as the O VI$\lambda$1038 Å 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 3.5 instead represents a lower limit on $\log N_H$ for models consistent with the O VI observations. This region of acceptable models includes the fiducial solution described above as well as a large class of models with $\log U \gtrsim -0.8$ 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 my claim of constant N/C at super-solar metallicities.

As mentioned, the expectation ($N \propto Z^2$) is only allowed at a lesser value of $\log U$ and $\log N_H$, which is in a region of parameter space still disallowed even when the measurement of O VI is considered a lower limit.

If instead I consider that the covering factor has been underestimated, increasing $C_f$ would decrease the derived column density of O VI. Models consistent with the new column density have smaller $\log N_H$ at fixed $\log U$. At most, however, I can decrease the column density by a factor of 2 by assuming a maximal covering fraction $C_f = 1.0$. In this scenario, the best model disagrees with both C IV and N V at the $4\sigma$ level (O VI at $3\sigma$) making all models with a solar mixture unacceptable. If I relax the solar mixture requirement for nitrogen (but retain it for carbon and oxygen), I 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
Thus, neither saturation nor too small a covering fraction affects the sense of my conclusion, only its magnitude. In all cases the expectation that nitrogen scales like the square of the bulk metallicity fails for System 1.

I now compare my 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 V/He II, N V/C IV, N V/O VI, and N V/(C IV+O VI). I also have a measurement of N IV], but Hamann et al. (2002) find that metallicities derived from it to be discrepant, as do I. I therefore exclude it from this comparison. Ratios involving N V do surprisingly well, indicating a gas metal rich by a factor of +0.7 to +0.8 dex on average, very close to my absorption line values using the standard AGN SED. It is curious, however, that these emission line models assume $N \propto Z^2$, inconsistent with the absorption line results, and still give the same bulk metallicity. Compared to the NLS1 SEDs which favor a much higher bulk metallicity, however, the emission line ratios fare rather poorly.

The results of my absorption-line analysis are somewhat surprising, not because of the super-solar 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 $Z^2$ ($[N/O]$
\( \propto [\text{O/H}] \) because the CNO cycle will preferentially convert Oxygen and Carbon into \(^{14}\text{N}\), enhancing Nitrogen relative to 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 Gyrs, and therefore have Nitrogen scaling as \( Z^2 \). There exists, then, a contradiction between my data and theory. If the analysis of my data is wrong, the extent of the error could be minimized by assuming the fault is limited to the \( \text{O} \, \text{VI} \) measurement. Using the F05 data only and assuming \( \text{N} \, \text{X} \, Z^2 \) find \( \log U \approx -1.8 \) as discussed above. To force agreement with these inferred physical conditions, \( \text{O} \, \text{VI} \) must be reduced in column density by a factor of 16. This is statistically unlikely, but there may be a hidden systematic effect that I have not discovered. Another way in which my analysis might be flawed is that I have assumed a simple absorber in my Cloudy models. System 1 may in fact be more complicated with a cooler cloud producing the \( \text{H} \, \text{I} \), \( \text{C} \, \text{IV} \), and \( \text{N} \, \text{V} \) absorption embedded in a hotter envelope producing the \( \text{O} \, \text{VI} \) 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 my 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 which would enhance the abundances and mixture to the values I 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 upon simple models of metal enrichment in galaxies. Another is that the existing models are simply not appropriate to this system. The theory which 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 upon. Additionally, I find that metal mixtures such as I find are not unprecedented for high metallicity stars. A recent study of planet-bearing and therefore statistically metal-rich stars by Ecuvillon et al. (2004) finds that [N/H] scales with [Fe/H] ($\frac{[N/H]}{[Fe/H]}$ slope is consistent with zero at the 2σ level) over the range $-0.4 < [Fe/H] < +0.4$. This study stops well short of the metallicity of Mrk 1044, but this is because the number of significantly super-solar stars simply runs out. significantly super-solar status of this Seyfert since the set of such stars simply subsides. Thus my 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.
Fig. 3.1.— FUSE spectrum of Mrk 1044. Identified absorption features are labeled: extragalactic sources above the spectrum and sources intrinsic to Mrk 1044 marked by their system (1 or 2), and local sources (ISM and instrumental) marked below the spectrum. Galactic H$_2$ absorption lines are identified by dotted lines. The dotted curves are my nine spline fits to the pseudo-continuum.
Fig. 3.2.— Velocity maps centered on the velocity of the absorption systems found in F05. System 1 (left) at −1158 and System 2 (right) at −286 km s$^{-1}$ match well with the velocities of −1158 and −286 km s$^{-1}$ found in F05. The line seen in Lyβ for System 1 is a blend of Lyβ and a Galactic H$_2$ line.
Fig. 3.3. — Velocity structure of the O VI doublet relative to the systemic velocity of Mrk 1044. The solid line traces O VI λ1032 Å while O VI λ1038 Å is traced by the dotted line. The dotted-line feature at $-1050 \text{ km s}^{-1}$ is a $z=0$ H$_2$ absorption line. The line at flux=1 represents the continuum of a perfect normalization and is provided for comparison. The data is binned to the FWHM of the instrument.
Fig. 3.4.— The 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 pseudo-continuum. The solid line is the spectrum after normalization but before H$_2$ subtracted whereas the dotted line shows the spectrum after the subtraction has taken place. The post-subtraction 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.
Fig. 3.5.— Cloudy models using its AGN template spectrum at many log $U$–log $N_H$ points assuming solar metallicity. Shaded regions indicate agreement with observed column densities at the 1σ 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 my measurement decreases as $C_f$ approaches the depth of the Lyα line ($\sim 0.75$). See Fig. 4 of Chapter 2 for an example of the normalized spectrum around Lyα. The metal lines all agree at log $U = -1.29$, log $N_H = 18.85$. $\Delta$ log $N_H$ is +0.7 relative to the preferred model for H I, +0.6 to the 1σ envelope of H I.
Fig. 3.6.— 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 $N_H$ plane. The H I component of the fit has been shifted by $-0.71$ dex to match the metal’s minimum at log $U = -1.29$, log $N_H = 18.85$. This implies a metallicity of $+0.71$ and thus a corrected log $N_H$ of 18.14.
Fig. 3.7.— The $\chi^2$ surface for Cloudy models at a bulk metallicity of five times solar with a solar mixture in metals and Helium enhanced by $\Delta Y/\Delta Z = 2$ 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 $N_H$ plane. The minimum lies at log $U = -1.20$, log $N_H = 18.13$, only slightly different than the inferred values from Figure 3.6.
<table>
<thead>
<tr>
<th>Line</th>
<th>Observed Wavelength [Å]</th>
<th>FWHM [km s(^{-1})]</th>
<th>Equivalent Width [mA]</th>
<th>log(Column) (^{a}) ([cm^{-2}])</th>
<th>log(Column) (^{b}) ([cm^{-2}])</th>
<th>Velocity [km s(^{-1})]</th>
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<tbody>
<tr>
<td>C II1036.337</td>
<td>1036.2431</td>
<td>83.9 ± 10.0</td>
<td>263 ± 33</td>
<td></td>
<td></td>
<td>−27 ± 8</td>
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<tr>
<td>C II*1037.018</td>
<td>1036.8348</td>
<td>236 ± 53</td>
<td>610 ± 180</td>
<td></td>
<td></td>
<td>−53 ± 8</td>
</tr>
<tr>
<td>O I1039.230</td>
<td>1039.2248</td>
<td>53.5 ± 4.2</td>
<td>183 ± 13</td>
<td>15.75(^{+0.10}_{-0.09})</td>
<td>15.56(^{+0.05}_{-0.06})</td>
<td>−2 ± 8</td>
</tr>
<tr>
<td>Ar II1048.220</td>
<td>1048.2091</td>
<td>17.8 ± 4.5</td>
<td>93 ± 14</td>
<td>13.73(^{+0.09}_{-0.10})</td>
<td></td>
<td>−3 ± 8</td>
</tr>
<tr>
<td>Fe II1055.2617</td>
<td>1055.2443</td>
<td>25.0 ± 4.8</td>
<td>58 ± 12</td>
<td>15.06(^{+0.10}_{-0.12})</td>
<td></td>
<td>−5 ± 8</td>
</tr>
<tr>
<td>Fe II1063.1764</td>
<td>1063.1610</td>
<td>72 ± 17</td>
<td>213 ± 41</td>
<td>15.16(^{+0.39}_{-0.30})</td>
<td></td>
<td>−4 ± 8</td>
</tr>
<tr>
<td>H(_2)</td>
<td></td>
<td></td>
<td></td>
<td>≈ 16.9(^{c})</td>
<td></td>
<td>≈ 0</td>
</tr>
</tbody>
</table>

\(^{a}\)Derived from the Curve-of-Growth Method

\(^{b}\)Derived from the Apparent-Optical-Depth Method

\(^{c}\)By-eye choices fluctuated between (7-8)\(\times10^{16}\) cm\(^{-2}\)

Table 3.1. Galactic Absorption Features.
<table>
<thead>
<tr>
<th>Ion</th>
<th>$\lambda_{Rest}$ [Å]</th>
<th>Equivalent Width [Å]</th>
<th>FWHM [km s$^{-1}$]</th>
<th>Velocity [km s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>N III</td>
<td>990</td>
<td>0.68 ± 0.15</td>
<td>341 ± 54</td>
<td>−190 ± 8</td>
</tr>
<tr>
<td>N III</td>
<td>992</td>
<td>0.55 ± 0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H I</td>
<td>1026</td>
<td>5.66 ± 3.65</td>
<td>3400 ± 1000</td>
<td>−314 ± 8</td>
</tr>
<tr>
<td>O VI</td>
<td>1032 Narrow</td>
<td>3.78 ± 0.53</td>
<td>656 ± 45</td>
<td>−494 ± 8</td>
</tr>
<tr>
<td>O VI</td>
<td>1032 Broad</td>
<td>25.7 ± 5.1</td>
<td>3720 ± 480</td>
<td>−880 ± 8</td>
</tr>
<tr>
<td>O VI</td>
<td>1038 Narrow</td>
<td>6.10 ± 0.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O VI</td>
<td>1038 Broad</td>
<td>13.1 ± 4.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2. Emission Line Properties of Mrk 1044.
<table>
<thead>
<tr>
<th>Line</th>
<th>Observed Wavelength [Å]</th>
<th>FWHM Width [km s(^{-1})]</th>
<th>Equivalent Width [mA]</th>
<th>$\log(\text{Column})_{a}$</th>
<th>$\log(\text{Column})_{b}$</th>
<th>Velocity [km s(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ly(\gamma)(^c)</td>
<td>984.82</td>
<td>50 ± 12</td>
<td>135 ± 37</td>
<td>&lt; 15.00</td>
<td>14.60</td>
<td>−1175 ± 8</td>
</tr>
<tr>
<td>Ly(\beta)</td>
<td>1038.5757</td>
<td>69 ± 3</td>
<td>244 ± 14</td>
<td>≥ 15.12(\pm)0.16</td>
<td>14.93(\pm)0.49(\pm)1.93</td>
<td>−1153 ± 8</td>
</tr>
<tr>
<td>O VI1032</td>
<td>1044.9335</td>
<td>61 ± 3</td>
<td>210 ± 15</td>
<td>≥ 15.08(\pm)0.14</td>
<td>14.92(\pm)0.08(\pm)0.10</td>
<td>−1150 ± 8</td>
</tr>
<tr>
<td>N III990(^c)</td>
<td>1002.291</td>
<td>92 ± 7</td>
<td>341 ± 5</td>
<td>14.20(\pm)0.09(\pm)0.12</td>
<td>−1156 ± 7</td>
<td></td>
</tr>
<tr>
<td>N III992(^c)</td>
<td>1004.103</td>
<td>92 ± 7</td>
<td>341 ± 5</td>
<td>14.20(\pm)0.09(\pm)0.12</td>
<td>−1156 ± 7</td>
<td></td>
</tr>
<tr>
<td>Ly(\alpha)</td>
<td>1230.9819</td>
<td>71 ± 3</td>
<td>209 ± 8</td>
<td>14.42(\pm)0.02(\pm)0.02</td>
<td>−1143 ± 6</td>
<td></td>
</tr>
<tr>
<td>N V1239</td>
<td>1254.4633</td>
<td>71 ± 3</td>
<td>162 ± 6</td>
<td>14.51(\pm)0.02(\pm)0.03</td>
<td>−1143 ± 6</td>
<td></td>
</tr>
<tr>
<td>N V1243</td>
<td>1258.4999</td>
<td>50 ± 6</td>
<td>204 ± 5</td>
<td>13.94(\pm)0.02(\pm)0.03</td>
<td>−1147 ± 5</td>
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</tr>
<tr>
<td>C IV1549</td>
<td>1567.7329</td>
<td>47 ± 5</td>
<td>156 ± 4</td>
<td>14.04(\pm)0.02(\pm)0.02</td>
<td>−1143 ± 5</td>
<td></td>
</tr>
<tr>
<td>C IV1551</td>
<td>1570.3602</td>
<td>47 ± 5</td>
<td>156 ± 4</td>
<td>14.04(\pm)0.02(\pm)0.02</td>
<td>−1143 ± 5</td>
<td></td>
</tr>
<tr>
<td>Sys 2: O VI1032</td>
<td>1047.8857</td>
<td>24 ± 8</td>
<td>41 ± 10</td>
<td>13.57(\pm)0.10(\pm)0.13</td>
<td>−295 ± 8</td>
<td></td>
</tr>
<tr>
<td>Sys 2: O VI1038</td>
<td>1053.7330</td>
<td>16 ± 13</td>
<td>18 ± 16</td>
<td>13.48(\pm)0.29(\pm)0.89</td>
<td>−276 ± 8</td>
<td></td>
</tr>
</tbody>
</table>

\(^{a}\)Derived from the Curve-of-Growth Method with \(b = 20\) km s\(^{-1}\)

\(^{b}\)Derived from the Apparent-Optical-Depth Method

\(^{c}\)3σ upper limits

Table 3.3. Measured and Calculated Parameters of Mrk 1044.
Chapter 4

CHANDRA Observations of Markarian 279

4.1. Introduction

Having determined the bulk metallicity and relative abundances of a NLS1, the field is best served by expanding my absorption-line study to other types of AGN. For this reason, I present results on the nearby (z=0.03) broad-line Seyfert 1 galaxy Mrk 279. This AGN was simultaneously observed by HST, FUSE, and CHANDRA. The results from the HST and FUSE observations are published in Gabel et al. (2005) and in Arav et al. (2005). Kaastra et al. (2004) studied the O V K-shell absorption lines in the CHANDRA spectrum, and while the significance of these lines is weak, they limit the distance of this absorber from the continuum source to light-weeks to light-months. Costantini et al. (2005) detects a two-components absorption system in the CHANDRA LETG spectrum. In that conference proceeding they find one low ionization component with a total column density $N_H \sim 1.6 \times 10^{22} \text{cm}^{-2}$ and a higher ionization component with a column density twice as high. These authors find outflow velocities for these two systems of $-220^{+50}_{-90}$ and $-570^{+100}_{-70} \text{km s}^{-1}$ respectively.
Y. Krongold has recently developed a program called PHASE (see below) with the goal of understanding photoionized plasmas such as found in the circumnuclear regions of AGNs. PHASE has been highly successful in its application to the \textit{CHANDRA} spectrum of NGC 3783 (Krongold et al. 2003, 2004), NGC 985 (Krongold et al. 2005), and the XMM spectra of NGC 4051 (Krongold et al. 2006). In NGC 3783 they found an absorbing outflow with two ionization components in pressure balance. They were able to accurately determine the size of the warm absorber for the first time in NGC 4051 by combining the detailed spectral model from the RGS data to the variability observed in the EPIC data. With accurate PHASE modeling, I am in a position to rule out some models of AGN outflow such as those with a continuous range of ionization parameters and those in which the absorption arises in extended, kpc-scale structures.

This chapter presents my PHASE analysis of the archival \textit{CHANDRA} spectrum of Mrk 279 from the 2003 observing campaign. Combined with available UV spectroscopy, this data cover a wide wavelength range, with multiple ionization states of many elements are detected. This allows me to constrain the physical state of the absorber. The connection between the X-ray and the UV absorber can also be tested. My goals here are as follows: (1) to constrain the physical conditions in the Mrk 279 outflow using \textit{CHANDRA} data, (2) to compare the results to the UV absorption system reported in Gabel et al. (2005), (3) to compare my results with
the preliminary results of Costantini et al. (2005), and (4) to compare the Mrk 279 system with other AGN outflows.

4.2. Observations and Data Reduction

Mrk 279 was observed seven times by the CHANDRA X-ray observatory in UTC 2003 May, with the low energy transmission grating (LETG) and the high resolution camera spectroscopic array (HRC-S) for a total of 340 ks of exposure time. The full details of the observations and data reduction are presented in Williams et al. (2006) where the Galactic ($z = 0$) absorption system along the line of sight to Mrk 279 is discussed. The focus of this paper is on the intrinsic absorption line system of Mrk 279. Spectral orders from $-6$ to $+6$ were included in the combined instrumental response matrix in order to model the continuum accurately. I note here that the resulting coadded LETG spectrum has a signal-to-noise ratio of $S/N \sim 6.5$ near 22Å, and the $S/N$ is comparable over the wavelength range of 10–50Å. The typical LETG/HRC-S resolution is about 0.05Å (FWHM), or 600 km s$^{-1}$ at 25Å. The 10–50Å spectrum is shown in Figure 1 of Williams et al. (2006).

4.3. Analysis

I conduct my analysis using Sherpa (Freeman et al. 2001) which is a part of the CIAO (Chandra Interactive Analysis of Observations; Fruscione 2002) package.
The global fit to the spectrum is performed using the recently-developed PHASE (PHotoionized Absorber Spectral Engine) program that self-consistently reproduces the X-ray absorption spectrum of an absorber intrinsic to the system. A detailed description of PHASE is given (Krongold et al. 2003): briefly, here. PHASE calculates absorption due to an ionized plasma using an extensive atomic database. The ionization balance is calculated using the CLOUDY code (version 90.04; Ferland 1997). As in CLOUDY, the incident continuum is from the AGN and a simple plane parallel geometry of absorber is assumed. PHASE calculates both bound-bound and bound-free transitions, with \( \sim 4000 \) lines including Fe L-shell transitions and the Fe M-shell UTA (Unresolved Transition Array) lines. At its simplest, an absorption-line spectrum can be fit with PHASE using only three input parameters: the equivalent hydrogen column density (\( \log N_H \)), the ionization parameter (\( \log U \)), and the wavelength centroid (expressed as the redshift of the absorber, \( z \)). This model is also capable of fitting the velocity widths and the individual abundances of most pre-iron elements, although these are less well constrained than the primary parameters.

The observed continuum of Mrk 279 is reasonably fit with a single powerlaw and Galactic absorption column density of \( N_H(\text{Gal}) = 1.78 \times 10^{20} \text{ cm}^{-2} \) as found in Williams et al. (2006). I allow the value of the Galactic absorption and the powerlaw slope to vary freely. The Galactic \( N_H \) value is fixed in practice as the variation in this parameter is small from solution to solution. The powerlaw slope must be allowed to vary freely as high metal-ion column densities can have significant
broad-band absorption effects. I tried fits to a continuum with the additional degree of freedom of a broken powerlaw, but the result was a fit with the break at 0.06 keV, below the observed energy range, indicating that this additional degree of freedom is unnecessary. In all my models I shall report results with a single powerlaw continuum plus Galactic absorption. To this continuum model I add one (and later a second) PHASE absorber. Even with just the 2-component continuum model alone, the fit is good ($\chi^2 = 3020$ for 3198 degrees of freedom). As I show below, however, the fit improves significantly when an absorbing component is added. The strong 21.6 Å line in the spectrum of Mrk 279 is from O VII $\text{K}\alpha$ at redshift zero absorber as reported by Williams et al. (2006). In what follows I will discuss only the warm absorber intrinsic to Mrk 279.

4.3.1. MRK 279 LIP ABSORBER

The most prominent absorption lines in the spectrum of Mrk 279 are those of C V, N VI, and O VII, all of which indicate the presence of a low-ionization absorber, similar to the low ionization phase (LIP) component observed in the spectra of other warm absorbers (e.g. NGC 3783; Krongold et al. 2003 and Netzer et al. 2003). I therefore first try to fit the absorption spectrum with a single absorber. The quality of the fit will determine whether I must add additional components, and whether an additional component will improve the fit significantly. For my single-absorber fit, I use the PHASE model, and only allow three parameters to vary: the ionization
parameter \( \log U \), the Hydrogen column density \( N_H \), and the absorber redshift \( z \); the continuum parameters are also allowed to vary. I fix the velocity width of the absorber to 200 km s\(^{-1}\) to avoid the problems discussed in Krongold et al. (2003), and the abundances are fixed to Solar values.

The existence of an absorber is heavily favored with a \( \Delta \chi^2 \approx 120 \) for a solar-abundance absorber. This absorber has best fit parameters of \( \log U = -1.07 \), \( \log N_H = 20.0 \), and an outflow velocity relative to systemic of 280 km s\(^{-1}\). This solution is robust to initial conditions. The value of the ionization parameter is indeed low, so I will refer to this absorber solution as the “low-ionization phase (LIP) component.” I tested the LIP absorption solution for its sensitivity to the abundance of each element and found that the LIP is most sensitive to the absorption lines of Carbon, Nitrogen, Oxygen, and the UTA of Iron. While the aggregate properties of all other elements influences the \( \Delta \chi^2 \) of the solution, the strengths of their individual lines are not significant. These elements and their ions simply do not have the cross-section or column densities to individually affect the LIP solution. In particular, I have no discriminatory power for Helium, Aluminum, Silicon, Argon, Calcium, and Nickel. A few remaining elements supported by PHASE are marginally seen, with slight evidence for Neon absorption (although the data are also consistent with continuum at these wavelengths). Possible Magnesium absorption is also seen, but these lines are at a location in the spectrum where the continuum is not well determined; as a result, Magnesium absorption does not have any diagnostic power.
Absorption lines of Carbon, Nitrogen, and Oxygen (C V, N VI, and O VII) are dominant contributors to the LIP, with tens of $\Delta \chi^2$ each, while Iron contributes substantially with its UTA. Allowing the abundance of these four elements to vary provides an additional $\Delta \chi^2 \approx 65$ and shifts the absorber parameters to $
abla \nabla \log U = -1.94$, $
abla \log N_H = 19.8$. All four require some degree of super-solar abundance, but this is not a robust result because the hydrogen column density in the warm absorber is not well constrained. The allowed range of abundances is twice Solar for Carbon to five times Solar for Nitrogen and Iron to eight times Solar for Oxygen. Extreme levels of enrichment (> 10 times Solar) are ruled out by a lack of observed strong absorption edges (such as C V). The parameters of these fits are given in Table 4.1. According to the F-test, addition of the LIP improves the spectral fit significantly, but there is no strong evidence for super-solar metallicity.

4.3.2. Mrk 279 HIP Absorber

The best fit LIP single-absorber solution systematically underpredicts several lines, the most prominent of which is O VIII K $\alpha$, and also underpredicts the amount of absorption blueward of the Fe-UTA. This observation, again, is similar to that in NGC 3783, and suggests the presence of a higher-ionized phase (HIP) absorber component. While the LIP solution can be modified to fit the Hydrogen-like lines of Carbon, Nitrogen and Oxygen by increasing the column densities of these elements, doing so severely overpredicts the amount of absorption due to the Helium-like ions.
For this reason I add a second absorber to my model, but constrain its metallicity to be identical to that of the LIP. In a similar manner to the process of fitting the LIP alone, I allow the metallicity of Carbon, Nitrogen, Oxygen, and Iron to vary but fix all other abundances to solar. There are then three new degrees of freedom: log $U_{HIP}$, log $N_{H,HIP}$, and outflow velocity $z_{HIP}$.

The addition of this component has $\Delta \chi^2 \approx 16$ indicating that it is significant according to the F-test. A comparison of this model and the single-absorber model is shown in Figure 4.1. However, depending on the initial conditions, there are two solutions: log $U_{LIP} = -1.9$, log $N_{H,LIP} = 19.8$, log $U_{HIP} = +0.3$, log $N_{H,HIP} = 19.3$ and log $U_{LIP} = -2.1$, log $N_{H,LIP} = 19.8$, log $U_{HIP} = -0.9$, log $N_{H,HIP} = 19.4$. Realizations of the second solution tend to be $2 - 3\chi^2$ lower than realizations of the first solution, but as individual realizations of either solution have a scatter of $1 - 2\chi^2$ I consider both equivalent. I prefer the former solution, as it maintains the physical parameters of the LIP found in the single-absorber model. Typical $1\sigma$ uncertainties on log $N_H$ are about $^{+0.3}_{-1.0}$ and on log $U$ are about ±0.05 for the LIP and ±0.2 for the HIP.

I can also compare the differences in metal columns between the single absorber system and the dual-absorber system, specifically between the corresponding LIPs; significant departures would indicate that the model is not robust. I find that adding a second component at most doubles the total column of a particular element; the usual difference is 40 – 50%. The $\Delta \chi^2$ of 16 realized in going from
a one-absorber model to a two-component model is entirely contained within the
10 – 30Å wavelength range. This indicates that the Carbon lines (C V and C VI) do not contribute significantly to the HIP. Oxygen and Iron then are the primary drivers in the need for an HIP. Predictably then, the metal columns of Carbon and Nitrogen in the LIP in both the single and dual absorber models are consistent with each other. As the abundances of the two absorbers are constrained to be the same, the HIP simply assumes the metallicity that the LIP demands.

4.4. DISCUSSION AND CONCLUSIONS

One somewhat surprising result is that I find that Neon is underabundant with respect to Oxygen. I report only upper limits on the Neon column density because the significance of detection for any one line is small, especially if the continuum is not adequately determined. Even so, the limits I am able to set are meaningful if only because of the high abundance of Oxygen. I find that the gas in the circumnuclear regions of Mrk 279 has a Ne/O ratio < 0.10, if not < 0.04, with respect to Solar. This is different from the intergalactic medium around the Galaxy where Ne is found to be overabundant with respect to Oxygen (Williams et al. 2005; Nicastro et al. 2002).

The total Hydrogen column density derived by adding together the two phases detected in the X-ray spectrum is less than $10^{20} \text{cm}^{-2}$. This is a smaller column
density than most known AGN outflows. It is unlikely that there is a significant amount of absorbing column in any other temperature phase, as all of the major absorption features are reasonably fit by the LIP and HIP combination. While some absorption features suggest an additional component (Silicon and Sulfur are best fit by an absorption system at \( \log U \sim -0.6 \)), the overall difference in \( \chi^2 \) does not demand the addition of more free parameters.

I can also compare my results to that of Gabel et al. (2005) who looked at the absorption in UV wavebands covered by FUSE and HST simultaneously with the X-ray observations. They find column densities for two absorption systems, each with lines of \( \text{H I} \), \( \text{C IV} \), \( \text{N V} \), and \( \text{O VI} \), for two models (A & B) with varying covering fractions. Gabel et al. (2005) identify multiple velocity components for each absorption line, none of which can be resolved in the X-ray spectrum of Mrk 279. As a result, I will consider the total column density of each ion in their models A & B. Since Gabel et al. (2005) do not discuss a photoionization model that best fits their ionic column densities, and since PHASE does not yet have the capacity to include UV/FUV spectra, I constructed Cloudy models and looked for solutions to test the consistency with my X-ray results. Without detailed knowledge of the data reduction process I assign conservative 25% uncertainties to each of their column density measurements.

I created Cloudy models with a Solar abundance and Solar mixture, and with the average AGN SED (table agn). The model grid was used to search for models
with predictions consistent with all four measured ionic column densities. While the \( \text{N} \, \text{V} \) and \( \text{O} \, \text{VI} \) columns are lower limits in most of the models, both provide information if there is also an \( \text{H} \, \text{I} \) measurement. I then note which \( \log U - \log N_H \) values produce models with column densities consistent with observations; this process is similar to that presented in Fields et al. (2005a,b). Recall that I have assigned uniform conservative uncertainties to these column densities and thus the best-fit model should only be considered “plausible” at best. For models A and B and to within uncertainties of \( \pm 25\% \), I find a stripe of acceptable models that stretch from \( \log U = -0.5 \), \( \log N_H = 19.7 \) (both models) to \( \log U = +0.5 \), \( \log N_H = 20.9 \) (model A) or \( \log U = -0.1 \), \( \log N_H = 19.9 \) (model B). In both cases the \( \text{N} \, \text{V} \) lower limit provides a stringent constraint while the \( \text{O} \, \text{VI} \) does not.

In my analysis I have made the assumption that the absorber has a solar mixture and abundance. If I relax this constraint, the range of acceptable models can be extended down to \( \log U \sim -1.9 \), \( \log N_H \sim 18.0 \) which is possible given solar or slightly subsolar Carbon \((-0.2 \, \text{dex})\) and up to heavily supersolar nitrogen and oxygen \((10 \, \text{times solar})\). Of course if the true column density uncertainties are larger or smaller, the range of acceptable models will expand or contract. Gabel et al. (2005)’s doublet method model has consistent Cloudy models from \( \log U = -1.0 \), \( \log N_H = 19.3 \) to at least \( \log U = +2 \), \( \log N_H = 23 \) and most likely beyond. The Full Coverage model (where it was assumed that the covering fraction \( C_f = 1 \) everywhere) has best-fit parameters of \( \log U = -1.1 \), \( \log N_H = 18.8 \) with Carbon
and Oxygen at Solar abundance and Nitrogen just slightly supersolar (+0.2 dex).
However, because the range of Cloudy models cannot be constrained by the doublet
method absorption model, and because of Gabel et al. (2005)’s justified distrust of
the Full Coverage model, I do not consider them further. The allowed parameter
space for models A & B is shown in Figures 4.2 & 4.3.

For the allowed values of log $U$ and log $N_H$ I then calculate the column density
of ions present in the X-ray spectrum. I find that the range of Cloudy models
supported by both models A and B have column densities of hydrogen and carbon
consistent with those I find in the X-ray. In addition, the lower limits found for
nitrogen and oxygen are also consistent with the column densities I measure, being at
most one dex below my values. However, the value of log $U$ in my X-ray absorption
model ($-1.95$) is grossly smaller than that found for the UV absorption lines ($-0.5$
to $+0.5$). I have not yet found a solution to this problem.

I also note that the hydrogen column density as measured in the UV/FUV
spectrum using model B is within the range inferred from the X-ray spectrum, but
the UV value is much more robust and more stringent. If I assume this UV value of
hydrogen column density ($\log N_H = 19.6-19.9$), then the suggestion of super-solar
metallicity from the PHASE models becomes stronger.

The parameters of the ionized outflow that I find are different from the
preliminary report by Costantini et al. (2005) (§1). The total column density of the
ionized absorber that I find \((\log N_H = 20.0)\) is lower by over two orders of magnitude for both the LIP and HIP. I note that my result is consistent with the UV value in Gabel et al. (2005). A total column density larger than \(10^{22} \text{ cm}^{-2}\), as in Costantini et al. (2005), is clearly ruled out by the lack of absorption edges. The Mrk 279 column density is much lower than that in other AGNS, e.g. NGC 3783 (Krongold et al. 2003), NGC 5548 (Mathur et al. 1995), or NGC 4051 (Krongold et al. 2006). In this sense, the outflow in Mrk 279 is the weakest known. The column density does not seem to be correlated with the source luminosity as the luminosity of NGC 4051 is a factor of one hundred less than that of Mrk 279.

I am slightly in conflict with the given velocities of the absorption systems given by Costantini et al. (2005). The velocities of both my absorption systems are each approximately 1.5\(\sigma\) less than their values. My LIP has an outflow velocity of \(280^{+50}_{-40}\) km s\(^{-1}\) compared to \(220^{+50}_{-90}\) km s\(^{-1}\), and my HIP has an outflow velocity of \(380 \pm 140\) km s\(^{-1}\) to \(570^{+100}_{-70}\) km s\(^{-1}\). This assumes I match my lower ionization parameter system with their lower ionization parameter system (and my higher with their higher). However, as can be seen the sense of the velocities match: both lower ionization components have smaller outflow velocities than both higher ionization components. These may not be in conflict at all. Furthermore, the HRC-S detector introduces distortions to the wavelength scale at certain points in the spectrum. A correction algorithm was included in the CIAO package at the end of December 2005, which was applied to my data. If Costantini et al. (2005) analyzed their data
before this correction was available, this could easily account for the differences in measured velocities.

Since I do not know the exact geometry and location of the warm absorber in Mrk 279, it is difficult to calculate its rates of mass and energy outflow. The location of the warm absorber in NGC 4051 is found to be 0.5–1.0 light days from the central source (Krongold et al. 2006). If the distance of the warm absorber from the nucleus scales as the square root of the luminosity, then, it would be about 5–10 light days for Mrk 279. Assuming a covering fraction of 10%, the mass outflow rate is $\sim 10^{-6} M_\odot$ yr$^{-1}$ and the kinematic luminosity is $\sim 3 \times 10^{34}$ erg s$^{-1}$. This wind is a negligible component of the AGN both bearing away a small fraction of the total mass accretion rate ($10^{-5}$) and carrying a small fraction of the radiative luminosity ($4 \times 10^{-11}$).

To summarize, I find that the warm absorbing outflow in Mrk 279 has two components in pressure balance with each other. The X-ray and UV absorbers appear to be parts of the same overall outflow. The outflow is very weak, however, and is unlikely to make any significant impact on the energy balance in the host galaxy or the surrounding intergalactic medium.
Fig. 4.1.— The region of the spectrum which gives weight to the HIP. In blue is the single absorber model (the LIP), and in red is the dual absorber model (LIP + HIP). Note that the HIP gives additional absorption blueward of 16Å and at O VIII Kα at 19.5Å.
Fig. 4.2.— Cloudy models using its AGN template spectrum at many $\log U - \log N_H$ points assuming solar metallicity. Colored points indicate agreement between Cloudy predicted column densities and observed Gabel et al. (2005) ionic columns from their system “2+2a”. Gabel et al. (2005) does not give uncertainties so I assign 25% errors. Red circles indicate agreement with H I, green hexagons indicate agreement with C IV, blue squares with N V lower limits, and purple triangles with O VI lower limits. The model parameters from $U = -0.5$, $N_H = 19.7$ to about $U = +0.5$, $N_H = 20.9$ provides acceptable fits to the data.
Fig. 4.3.— This time I look at Gabel's model B for absorber “2+2a”. Model B is their preferred model. Points are as in Figure 4.2. N V and O VI are still lower limits. The range of acceptable models is slightly less: $\log U = -0.5$, $\log N_H = 19.6$ to about $\log U = -0.1$, $\log N_H = 19.9$. As the N V curve represents a lower limit Nitrogen can be overabundant but is consistent with solar abundance. The gas can have a super-solar bulk metallicity assuming $\log U$ between 0 and +1.
### Table 4.1. Absorber Model Parameters.

<table>
<thead>
<tr>
<th>Model</th>
<th>log $U$</th>
<th>log $N_H$</th>
<th>log $N_C$</th>
<th>log $N_N$</th>
<th>log $N_O$</th>
<th>log $N_{Fe}$</th>
<th>$\Delta \chi^2/\Delta$ dof</th>
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</thead>
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<tr>
<td>Solar</td>
<td>-1.07</td>
<td>20.0</td>
<td>16.53</td>
<td>15.95</td>
<td>16.85</td>
<td>15.49</td>
<td>123/3</td>
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<tr>
<td>CNOFe Variable</td>
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<td>19.8</td>
<td>16.59</td>
<td>16.35</td>
<td>17.62</td>
<td>15.91</td>
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<tr>
<td>LIP</td>
<td>-1.93</td>
<td>19.8</td>
<td>16.58</td>
<td>16.37</td>
<td>17.57</td>
<td>16.04</td>
<td>16/3</td>
</tr>
<tr>
<td>HIP</td>
<td>+0.45</td>
<td>19.5</td>
<td>16.27</td>
<td>16.05</td>
<td>17.26</td>
<td>15.72</td>
<td>...</td>
</tr>
</tbody>
</table>

Column densities are in log cm$^{-2}$

### Table 4.2. Gabel et al. (2005) Comparison.

<table>
<thead>
<tr>
<th>Model</th>
<th>log $U$</th>
<th>log $N_H$</th>
<th>log $N_C$</th>
<th>log $N_N$</th>
<th>log $N_O$</th>
<th>log $N_{Fe}$</th>
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<tbody>
<tr>
<td>LIP</td>
<td>-1.93</td>
<td>19.8</td>
<td>16.58</td>
<td>16.37</td>
<td>17.57</td>
<td>16.04</td>
</tr>
<tr>
<td>A “2+2a”</td>
<td>-0.5+0.5</td>
<td>19.7–20.9</td>
<td>16.3–17.5</td>
<td>15.7–16.9</td>
<td>16.6–17.8</td>
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</tr>
<tr>
<td>B “2+2a”</td>
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<td>19.6–19.9</td>
<td>16.2–16.5</td>
<td>15.6–15.9</td>
<td>16.5–16.8</td>
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<tr>
<td>4a</td>
<td>-1.1+</td>
<td>18.8+</td>
<td>15.4+</td>
<td>14.8+</td>
<td>15.7+</td>
<td></td>
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<tr>
<td>HIP</td>
<td>+0.45</td>
<td>19.5</td>
<td>16.27</td>
<td>16.05</td>
<td>17.26</td>
<td>15.72</td>
</tr>
</tbody>
</table>

Column densities are in log cm$^{-2}$

Table 4.2. Gabel et al. (2005) Comparison.
Chapter 5

Conclusions

This work has shown that it is possible to measure well-constrained gas-phase abundances in AGN intrinsic absorption-line systems. Markarian 1044 currently has the best determined gas-phase metal abundances for any AGN. This is because of the broad UV wavelength coverage possible from orbiting observatories (spectra from both HST and FUSE), simple kinematics, high apparent brightness (good signal-to-noise), and high spectral resolution ($\delta \lambda / \lambda \approx 30,000$; the HST-STIS spectrum). Two outflowing systems were found in Markarian 1044, the stronger of which shows absorption lines of H I, C IV, N V, and O VI. Not only does this work show that this outflowing gas has a supersolar bulk metallicity, but it also shows that the gas has a Solar mixture of elements. This means that the enrichment processes operating in the Galactic disk must be different than those in the nuclei of this active galaxy, and by implication, perhaps in the nuclei of many active galaxies.

This work has also shown that relative metal abundances may be determined (if not to the precise degree of Markarian 1044) though use of the PHASE code. This code allows me to self-consistently analyze the many absorption lines found in
the X-ray part of the spectrum, allowing me to compensate for the fact that any one waveband is insufficient. Adding simultaneous FUSE or HST spectra allows us to convert relative metal abundances into absolute abundances through the UV H I lines. The AGN under study, the broad-line Seyfert 1 Markarian 279, is found to be consistent with solar abundances in scale, but not precisely in mixture. PHASE has proven its worth in reproducing the entire X-ray absorption spectra with a minimum of free parameters.

I now have precise and relatively precise measurements of absorption-line abundances in two AGN. This allows us to start to calibrate the more easily measured emission-line abundance indicators. These indicators are necessary for interpretation of the abundances of the highest-redshift quasars. In this way, the study of nearby relatively intermediate-luminosity AGN (Seyferts), can help inform us about the star formation history in the early universe. The more nearby AGN studied in absorption lines, the better calibrated the emission-line measurements can be. However, Markarian 1044 has shown that the assumptions (enrichment process) that go into the emission-line models does not work in every AGN. What must be done is to focus further absorption-line studies on other NLS1s in order to determine whether Markarian 1044 is unique or part of a larger fraternity of AGN with unusual star formation histories.
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