**FUSE Spectroscopy of High Velocity Cloud Complex C**

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**ABSTRACT**

We present *Far Ultraviolet Spectroscopic Explorer* (FUSE) observations of the sightline toward the Seyfert 1 galaxy Markarian 876, which passes through high velocity cloud (HVC) complex C. This sightline demonstrates the ability of *FUSE* to measure ionic absorption lines in Galactic HVCs. High velocity absorption is clearly seen in both members of the O VI doublet. This is the first detection of O VI in a neutral hydrogen HVC. One component of HVC complex C is resolved in multiple Fe II lines from which we derive N(Fe II)/N(H I)=0.48 (Fe/H). This value of N(Fe II)/N(H I) implies that the metallicity of complex C along this sightline may be higher than that along the Mrk 290 sightline (0.1 solar) found by Wakker et al. (1999). On the other hand, if the metallicity of complex C is also 0.1 solar along this line of sight, the observed value of N(Fe II)/N(H I) suggests there may be a significant amount of H\(^+\) along the line of sight. In any case, little, if any, iron can be depleted into dust grains if the intrinsic metallicity of complex C is subsolar. Absorption from complex C is also seen in C II, N I, and N II, and upper limits based on non-detections can be determined for Ar I, P II, and Fe III. Although molecular hydrogen in the Milky Way is obvious in the *FUSE* data, no H\(_2\) absorption is seen in the high velocity cloud to a limit N(H\(_2\))< 2.0 \times 10\(^{14}\) cm\(^{-2}\). Future *FUSE* observations of extragalactic objects behind Galactic high velocity clouds will allow us to better constrain models of HVC origins.

Subject headings: ISM: abundances—Galaxy: abundances—Galaxy: general

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1. INTRODUCTION

Despite significant observational and theoretical efforts over nearly 40 years of study, the nature of Galactic H I high velocity clouds (HVCs) is still a mystery. With the launch of the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*), a new and important portion of the electromagnetic spectrum is now available to study HVCs. The far-ultraviolet provides a wealth of atomic, ionic, and molecular spectral lines that can be used to probe the physical conditions in HVCs (Sembach 1999). With its high resolution and large effective area, *FUSE* has the ability to probe HVCs along multiple lines of sight toward extragalactic objects. This paper presents an analysis of such a sightline and demonstrates the ability of *FUSE* to significantly contribute to our understanding of HVCs.

The sight line to Mrk 876 (\(l = 98^\circ27, b = 40^\circ38\)) passes through HVC complex C (Wakker & van Woerden 1991). Wakker et al. (1999) suggest the distance to complex C is in the range of 5-25 kpc, with D \sim 10 kpc as the most likely value. They derive a mass for complex C of \(6 \times 10^6 \; M_\odot \; (D/10 \; kpc)^2\) which, combined with the observed radial velocity, implies a mass influx of \(0.08 - 0.19 \; (D/10 \; kpc) \; M_\odot \; yr^{-1}\). The metallicity of complex C is in the range 0.1 to 0.6 solar (Wakker et al. 1999; Gibson et al. 2000) and may be spatially variable toward multiple sightlines separated by more than \(10^5\). The metallicity of HVCs can be used to discriminate between the current theories for their origins (van Woerden et al. 1999).

Along the Mrk 876 sightline, a 21 cm spectrum taken with the Effelsberg 100 m telescope with a 9.7 beam shows two components at \(V_{LSR} = -172 \; km \; s^{-1}\) and \(V_{LSR} = -133 \; km \; s^{-1}\) with N(H I)= \((4.1 \pm 0.8) \times 10^{18} \; cm^{-2}\) and N(H I)= \((19.2 \pm 0.8) \times 10^{18} \; cm^{-2}\), respectively. An NRAO 140 Foot Telescope (43 meter) observation with a 21' beam gives a column density that is 2.2 times higher than the Effelsberg spectrum for the \(-172 \; km \; s^{-1}\) component while both telescopes give identical results for the \(-133 \; km \; s^{-1}\) component. The difference between the 9.7' and 21' results probably arises from small scale structure in the HVC, since it is much larger than any expected statistical uncertainties or calibration differences. We have used the Effelsberg spectrum in the analysis that follows.

An H\(_\alpha\) spectrum obtained by M. Haffner (private communication) with the WHAM instrument (Reynolds et al. 1998) indicates that the H\(_\alpha\) intensity associated with complex C toward Mrk 876 is < 0.02 R (1 R is \(10^6\) photons cm\(^{-2}\) (4 \(\pi r^2\))\(^{-1}\) averaged over the 1' beam of the instrument. Complex C is clearly detected in other directions (Wakker et al. 1999; Tufte et al. 2000, in preparation).
which implies a patchy distribution of N(H$^+$). Since both the distance to complex C and the geometry of the emitting region are unknown, and there may exist small scale structure in the large WHAM beam, no meaningful limit can be placed on N(H$^+$) at this time.

2. **FUSE Observations**

For a description of the **FUSE** satellite, its operation, and observing modes see Moos et al. (2000) and Sahnow et al. (2000). The Mrk 876 dataset (P1073101) consists of 10 consecutive exposures in the $30^\prime\prime$ × $30^\prime\prime$ apertures, resulting in 52 ksec of on-target integration. At the time of the observations (16 October 1999) the spectrograph was not yet aligned or focused. The target appears in both LiF channels and one SiC channel. The data were passed through the standard CALFUSE pipeline, which removed the spectral motion, performed a background subtraction, removed the geometric distortions, extracted the spectra, and performed wavelength and flux calibrations. Event bursts were removed from the data by hand. Coaddition of the channels was not attempted due to the preliminary nature of the wavelength calibration. Typically, the equivalent width of an absorption line was measured separately for each channel and averaged. The typical spectral resolution was $\lambda/\Delta\lambda \approx 12000$. The average S/N is 14:1 per resolution element in the LiF1 channel, 17:1 in the LiF2 channel, and 8:1 in the SiC1 channel.

3. **First Detection of an O VI HVC**

The O VI lines are shown in Figure 1. Absorption from HVC complex C is clearly present at negative velocities as high as $-215 \text{ km s}^{-1}$. O VI is an excellent tracer of hot gas (2–5 × $10^5 \text{ K}$) and is not generally produced by photoionization. Beyond $-215 \text{ km s}^{-1}$ the O VI 1031.93 Å line is blended with the Galactic H$_2$ (6-0) P(3) line at 1031.19 Å. Fortunately, the H$_2$ line is narrow and was easily removed from the spectrum. Integrating the profile between $-215 \text{ km s}^{-1}$ and $-100 \text{ km s}^{-1}$ we find and equivalent width of 146 ± 14 mÅ which implies N(O VI) = (1.5 ± 0.2) × 10$^{14}$ cm$^{-2}$ if the line is optically thin. High velocity absorption is also seen in the O VI 1037.62 Å line; however, it is blended with the strong Galactic H$_2$ (5-0) R(1) line at velocities more negative than $-140 \text{ km s}^{-1}$, making a column density measurement impossible.

The amount of hot gas implied by the O VI detection can be significant if the metallicity of complex C is low. The models of Sutherland & Dopita (1993) give the ionization fraction of O VI as function of temperature for gas in collisional equilibrium. At the peak of the O VI ionization fraction (22% at 280,000 K), the amount of hot gas is N(H$^+$) $> 7 \times 10^{17}$ cm$^{-2}$ (O/H)$_0$/(O/H)$_{HVC}$. A discussion of the possible interpretations for the detection of high-velocity O VI in complex C and other HVCs is presented by Sembach et al. (2000).

4. **Metal Lines in Complex C**

Metal line absorption associated with the $-133 \text{ km s}^{-1}$ H I component (and, in some cases, the $-172 \text{ km s}^{-1}$ component) is seen in several Fe II lines, C II, N I, and N II. Upper limits can be set for Ar I, P II, and Fe III. Example absorption lines are presented in Figure 1. Table 1 lists the measured equivalent widths, column densities and derived abundances relative to the solar values. The errors are a combination in quadrature of the statistical error, based on the S/N ratio of the spectrum, and systematic errors calculated as the rms value of measurements made by different authors, by using different detector segments, different continuum placement, and by using subsets of the data (e.g., night-only).

Five HVC Fe II lines from the $-133 \text{ km s}^{-1}$ component are detected, from which a curve of growth can be derived. We minimize $\chi^2(N(b)=W(\lambda_{\text{observed}})^2 - W_b(N(b)^2)$, and find N = 3.0 ± 1.2 × 10$^{14}$ cm$^{-2}$ and $b=12.1 ± 5.6 \text{ km s}^{-1}$. All observed values of W$_b$ are then within 1σ of the expected value. We will use this b-value below to convert equivalent width to column density for other ions (excluding O VI). The $-172 \text{ km s}^{-1}$ component is also seen in absorption in Fe II $\lambda$1144.94. The Fe III $\lambda$1121.98 line from the $-133 \text{ km s}^{-1}$ component is absent, yielding N(Fe III)/N(Fe II) $< 0.22$.

N II $\lambda$1083.99 high-velocity absorption can clearly be seen in the SiC1 channel; however, the individual components are blended and the spectrum has low S/N. Integrating the line and apparent column density profiles between $-160$ and $-100 \text{ km s}^{-1}$ yields an equivalent width $>120 \text{ mÅ}$ and a column density of N(N II) $> 1.0 \times 10^{14}$ cm$^{-2}$. If we calculate the column density assuming the b value found above for iron, the result is a factor of three higher. The high-velocity component of N I $\lambda$1334.17 is blended with low-velocity Fe II $\lambda$1133.67. Using a curve of growth for the low velocity gas, we derive $W_b(\lambda_{\text{Fe II}}$ $\lambda$1133.67) $= 67 ± 7 \text{ mÅ}$. The measured width of the blend is 94 ± 7 mÅ, so that 27 ± 10 mÅ can be attributed to high-velocity N I. This matches, to within the errors, the column density of N I $\lambda$1199.55 found by Gibson et al. (2000) toward Mrk 876 using the Space Telescope Imaging Spectrograph on the *Hubble Space Telescope*.

C II $\lambda$1036.34 is clearly present in both components of the HVC and is strongly saturated. For P II $\lambda$1152.82 and Ar I $\lambda$1048.22 only 3σ upper limits of 25 mÅ can be set at this time.

5. **Metal Abundances in Complex C**

The observed ratio N(Fe II)/N(H I) $\sim 0.5$ (Fe/H)$_0$ is unexpected given that every previously studied sightline through cool, warm, or halo gas has shown iron depleted by at least a factor 3 (Savage & Sembach 1996). If the intrinsic metallicity of complex C is subsolar, then little, if any, iron can be depleted into dust grains. The iron abundance is also higher than the value of S/H$\sim 0.1$ (S/H)$_0$ found by Wakker et al. (1999) along the Mrk 290 sightline through complex C. Gibson et al. (2000) have measured S II absorption along the lines of sight to Mrk 817, where N(S II)/N(H I) = 0.3 (S/H)$_0$, and Mrk 279, where N(S II)/N(H I) $\sim 0.6$ (S/H)$_0$. They find that assuming the presence of H$^+$ along the line of sight is insufficient to reconcile their observations with the metallicity found by Wakker et al. (1999). Instead, they believe that the metallicity of complex C is spatially variable with metallicities ranging from 0.1 – 0.6 solar. The low abundance of argon (N(4Ar I)/N(H I) $< 0.13$ (Ar/H)$_0$) toward Mrk 876 is probably a photoionization effect; Ar I has a photoionization cross-section about 10 times larger than that of hydrogen (Sofia & Jenkins 1998). Upcoming **FUSE** observations of the Mrk 290, Mrk 817, and Mrk 279 sightlines should help
Fig. 1.— Ionic absorption lines as measured by *FUSE* along the line of sight to Mrk 876. For species that are covered by two or more channels, only one channel is shown. The wavelength scale was adjusted separately for each line by aligning the low-velocity absorption. Absorption from HVC complex C is clearly seen in the O\textsc{vi} 1031.93 Å line and Fe\textsc{ii} 1144.94 Å line.
resolve these issues.

6. LIMITS ON MOLECULAR HYDROGEN

Previous searches for molecular gas in high velocity clouds concentrated on tracers such as CO and HCO\(^+\), which have spectral lines at millimeter wavelengths. Wakker et al. (1997) and Akeson & Blitz (1999) placed upper limits on \(N(H_2)\) of \(9 \times 10^{18}\) cm\(^{-2}\) and \(5.5 \times 10^{18}\) cm\(^{-2}\) in several HVCs, respectively, assuming solar abundances and standard I(CO) to N(H\(_2\)) ratios. Richter et al. (1999) have reported the discovery of H\(_2\) absorption at a velocity of +120 km s\(^{-1}\) with \(N(H_2) = (2.2 - 3.6) \times 10^{15}\) cm\(^{-2}\) in an ORFEUS spectrum of the LMC star HD 269546 (Sk -68 82). However, this sightline is quite complicated, and has absorption associated with the Milky Way, the LMC, as well as the HVC.

FUSE can observe the far UV electronic transitions of molecular hydrogen from both the Lyman (B–X) and Werner (C–X) bands at high resolution toward many extragalactic objects behind HVCs. Toward Mrk 876, absorption lines from H\(_2\) in the Milky Way are readily visible with \(N(H_2) \sim 2.3 \times 10^{18}\) cm\(^{-2}\) (Shull et al. 2000). Figure 2 compares the observed spectra and the expected absorption signatures of the two components of complex C for an H\(_2\) column density of \(2 \times 10^{14}\) cm\(^{-2}\) in each component and for a rotational temperature of \(T_01 = 100\) K and \(b = 10\) km s\(^{-1}\). The selected lines are the strongest H\(_2\) lines in the FUSE bandpass that are not blended with other atomic or molecular lines. Clearly, there is no detectable H\(_2\) absorption from HVC complex C. Reasonable changes in \(T_01\) or \(b\) do not alter this conclusion. Since the most efficient mechanism for forming H\(_2\) is on the surfaces of dust grains (Spitzer 1978), the non-detection of H\(_2\), coupled with the low depletion of iron, implies that there is little or no dust in complex C along this line of sight.

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Fig. 2.— A comparison of the observed spectrum with expected absorption signatures of two components of $\text{H}_2$ with $V_{\text{LSR}} = -172$ km s$^{-1}$ and $V_{\text{LSR}} = -133$ km s$^{-1}$ each having $N(\text{H}_2) = 2.0 \times 10^{14}$ cm$^{-2}$ for a temperature $T_{01} = 100$ K and $b = 10$ km s$^{-1}$. If $\text{H}_2$ were present at this column density, it would have been observed.
| Ion | $\lambda^b$ | $f^b$ | $W_\lambda$ | N  | $(X^{+i}/H)^{\text{HVC}}/(X/H)_{\odot}^e$ |
|-----|-----------|-------|-------------|-----|-----------------------------------|
| N i  | 1134.165 | 0.0152 | 27±10     | 15.6±5.7 | 0.087±0.032 |
| N II | 1083.994 | 0.115  | >120      | >10   | >0.06 |
| O VI | 1031.926 | 0.133  | 146±14    | 15±2  | <1.2 |
| P II | 1152.818 | 0.245  | <25       | <0.87 | <0.13 |
| Ar I | 1048.220 | 0.263  | <25       | <0.98 | <0.13 |
| Fe II | COG      |       |           |       | 0.48±0.20 |
| Fe II | 1112.048 | 0.0065f | 27±15     |       |       |
| Fe II | 1121.975 | 0.0184f | 51±10     |       |       |
| Fe II | 1125.448 | 0.0156  | 41±2      |       |       |
| Fe II | 1143.226 | 0.0192  | 49±10     |       |       |
| Fe II | 1144.938 | 0.1090  | 129±16    |       |       |
| Fe II| 1144.938 | 0.1090  | 47±16     | 4.7±1.6 | 0.35±0.14 |
| Fe II| 1122.524 | 0.0540  | <40       | <6.6  | <0.11 |

\[a\] All measurements apply to the $-133 \text{ km s}^{-1}$ component (integration range $-160 \text{ km s}^{-1}$ to $-100 \text{ km s}^{-1}$) unless otherwise noted. Limits are 3σ estimates.

\[b\] Except where noted, wavelengths and oscillator strengths are from Morton (1991).

\[c\] Solar system abundances from Anders & Grevesse (1989).

\[d\] Equivalent width and apparent column density profile were integrated over the range $-160$ to $-100 \text{ km s}^{-1}$.

\[e\] Equivalent width and apparent column density profile were integrated over the range $-215$ to $-100 \text{ km s}^{-1}$.

\[f\] Oscillator strength from C. Howk, private communication

\[g\] Measurement applies to the $-172 \text{ km s}^{-1}$ component.