Highly Ionized High Velocity Clouds

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Abstract. We have recently used the Hubble Space Telescope to study a pair of high velocity clouds in the direction of Mrk 509 that have unusual ionization properties. They exhibit strong C\textsc{iv} absorption with little or no low ion absorption or H\textsc{i} 21 cm emission. As the closest known analog to the outer diffuse halos of damped Ly\alpha absorbers and the low N(H\textsc{i}) metal line absorption systems seen in the spectra of high redshift quasars, these “C\textsc{iv}-HVCs” may shed new light on the origins of some HVCs, as well as present opportunities for comparing absorption due to intergalactic gas in the local universe with absorption in moderate-high redshift gas clouds. The C\textsc{iv}-HVCs have ionization properties consistent with photoionization by extragalactic background radiation and a location within the Local Group. The presence of weak H\textsc{i}-HVCs detected through 21 cm emission within 2° of the sight line suggests that the C\textsc{iv}-HVCs trace extended, ionized, low density regions of the H\textsc{i}-HVCs. In this article we summarize the results of our study of the C\textsc{iv}-HVCs and suggest additional observations that would test the hypothesis of an intergalactic location for the clouds.

1. Introduction

Investigations of galactic chemical evolution and galaxy formation at moderate to high redshift have progressed rapidly in recent years due to spectroscopic observations from the ground and imaging campaigns with the Hubble Space Telescope (HST). To tie these studies into the present-day epoch, it is necessary to understand the processes that govern galactic evolution within the local universe. Determining the properties of high velocity clouds (HVCs), which typ-
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ic平 have velocities $|V_{\text{LSR}}| > 100$ km s$^{-1}$, may prove to be an important step in revealing the processes that distribute and ionize gases in the halos of the Milky Way and other galaxies. These clouds can be studied spectroscopically without confusion from lower velocity absorption if suitable background sources can be found.

There have been many ideas proposed to explain the distribution of HVCs on the sky and their kinematics, including supernova-driven “Galactic fountains” (Shapiro & Field 1976; Bregman 1980), ram pressure or tidal stripping of material from the Magellanic Clouds (Moore & Davis 1994; Lin et al. 1995), infalling gas from outside the Milky Way (Oort 1970; Mirabel & Morras 1984), and identification of HVCs as intergalactic clouds within the Local Group (Blitz et al. 1998). However, distinguishing between all of these possible scenarios has not been easy, despite many years of study (see Wakker & van Woerden 1997 for a review of HVC properties and possible origins).

Traditionally, HVCs have been studied through their H I 21 cm emission, but it is now possible to make fundamental advances in understanding HVCs by examining their absorption properties in detail with the HST. We have obtained a full suite of Goddard High Resolution Spectrograph (GHRS) absorption line observations to study the neutral and ionized gases in two HVCs in the direction of Mrk 509 ($l = 36.0^\circ, b = -29.9^\circ$). The clouds exhibit strong CIV absorption with little or no corresponding low ion (C II, Si II) absorption or H I 21 cm emission down to a detection threshold of log $N(\text{H I}) \approx 17.7$ (see Figure 1). These “CIV-HVCs” have ionization properties that are very different from those of gases in the Galactic disk and low halo (Sembach et al. 1995, 1999). Figure 1 shows that the low velocity ($|V_{\text{LSR}}| < 100$ km s$^{-1}$) gas in the Galactic disk and halo along the Mrk 509 sight line is characterized by both high ionization and strong low ionization absorption. This is typical for diffuse interstellar gases in the Milky Way (Sembach & Savage 1992), but is very different than the CIV-HVC absorption signature at $|V_{\text{LSR}}| \approx -340$ to $-170$ km s$^{-1}$, where the dominant absorbing ion is clearly CIV. To a large degree, the CIV-HVCs resemble the low column density (log $N(\text{H I}) < 17$) QSO metal line absorption systems, in which one often sees strong CIV (and sometimes SiIV) absorption but little low ionization absorption (Steidel 1990; Songaila & Cowie 1996).

2. Properties of the CIV-HVCs

Using the photoionization code CLOUDY (Ferland 1996), we modeled the CIV-HVCs toward Mrk 509 as slabs of gas bathed in extragalactic background radiation with a QSO spectral energy distribution and a mean intensity at the Lyman limit $J_{\nu}(\text{LL}) = 1 \times 10^{-23}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ (Haardt & Madau 1996). We show a sample model from Sembach et al. (1999) in Figure 2. In this model, the column densities are satisfied for a narrow range of ionization parameters, $\Gamma = n_e/n_H$. The combination of $\Gamma$ constrained by the ionic ratios and an assumption about $J_{\nu}(\text{LL})$, which is proportional to $n_e$, sets the density of the model cloud. The size, $D = N(\text{H})/n_H$, is also determined since the observed metal line column densities yield $N(\text{H})$ for a given metallicity.

We compared the observations to predictions of models involving collisional ionization or photoionization by starlight and found that the ionic ratios are
Table 1. Properties of the C\textsc{iv}-HVCs Toward Mrk 509$^a$

| $V_{\text{LSR}}$ (km s$^{-1}$) | $\log N(\text{H})$ (cm$^{-2}$) | $\log N(\text{H}\textsc{i})$ (cm$^{-2}$) | $n_H/n_{\text{H}\textsc{i}}$ | $\log n_H$ (cm$^{-3}$) | $T$ (K) | $P/k$ (cm$^{-3}$ K) | Diam. (kpc) |
|-----------------------------|-----------------|-----------------|-----------------|-----------------|--------|-----------------|---------|
| $-283$                      | 19.05           | 16.30           | 560             | $-3.82$         | 14,800 | $\sim 5$       | 28      |
| $-228$                      | 18.16           | 14.70           | 2900            | $-4.48$         | 19,200 | $\sim 1$       | 16      |

$^a$ Values in this table are appropriate for ionization of a uniform slab of material bathed in extragalactic background radiation at $z = 0$. The calculations are for a model with a metallicity of 1/3 solar and no dust. Lower metallicity models yield approximately the same results, except that the cloud sizes are proportionally larger. For example, the cloud diameters for [Z/H] = $-1$ are 108 and 62 kpc for the $-283$ and $-228$ km s$^{-1}$ clouds, respectively. Note the very low thermal pressures, which are much smaller than values for typical diffuse gas in the Milky Way where $P/k \sim 4 \times 10^3$ cm$^{-3}$ K.

most consistent with photoionization by extragalactic background radiation. If the gas is photoionized by the extragalactic background or a combination of ultraviolet starlight and the extragalactic background, the clouds must be low density ($n_H \sim 10^{-4}$ cm$^{-3}$), large (greater than several kiloparsecs), and mostly ionized ($n_{\text{H}\textsc{i}}/n_H \sim 10^{-3}$) regions located well beyond the neutral gas layer of the Galaxy. If the clouds are intergalactic in nature, their metallicities could be [Z/H] $\sim -1$ or lower. Table 1 contains a summary of the C\textsc{iv}-HVC properties, assuming [Z/H] = $-0.5$.

The low inferred pressures for the C\textsc{iv}-HVCs, $P/k \sim 1$–5 cm$^{-3}$ K, are strongly suggestive of an intergalactic origin. The pressures are 2–3 orders of magnitude smaller than those predicted for multi-phase models of the Galactic halo at $|z| < 10$ kpc (e.g., Wolfire et al. 1995).

3. The Origin of HVCs and Relevance to Galaxy Evolution

Blitz et al. (1998) have recently proposed the intriguing hypothesis that some of the observed H\textsc{i}-HVCs in the sky are large (diam $\approx 25$ kpc) dark-matter-dominated clouds located within the Local Group. Their argument for an extragalactic location for the clouds is based upon the good agreement between the velocity centroid of the cloud ensemble considered and that of the Local Group (see Blitz, this volume). They suggest that the Milky Way has accreted, and continues to accrete, such clouds. Such an accretion could have profound implications for the physical state of the Galactic halo and the chemical evolution of the Galaxy, since the infalling gas clouds in this model typically have masses of $\sim 10^8$ M$_\odot$. The kinematics and ionization of the C\textsc{iv}-HVCs toward Mrk 509 are consistent with the Blitz et al. (1998) model and suggest that an intergalactic origin for some HVCs may be possible. However, confirmation of an ensemble of such clouds will require further observations and tests, such as direct measurements of metallicities in the H\textsc{i}-HVCs.

The properties of the C\textsc{iv}-HVCs toward Mrk 509 are similar to the properties found for high redshift ($z \sim 3$) Ly$\alpha$ clouds with $10^{14} < N(\text{H}\textsc{i}) < 10^{17}$ cm$^{-2}$ and $\log \Gamma \approx -2.5$ to $-1.9$ (see Songaila & Cowie 1996). In recent cosmological
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Figure 1. **Top:** Brightness temperature versus LSR velocity for H\text{I} 21 cm emission toward Mrk 509 and two nearby positions on the sky. Note the absence of H\text{I} emission at high velocities directly along the sight line. **Bottom:** Continuum normalized intensity versus LSR velocity for the N\text{V} \lambda 1238, Si\text{IV} \lambda 1393, Si\text{III} \lambda 1206, Si\text{II} \lambda 1526, C\text{IV} \lambda 1548, and C\text{II} \lambda 1334 lines observed by Sembach et al. (1999) with the GHRS G160M grating (R \approx 20,000). Note the presence of strong C\text{IV} absorption at velocities between $-340$ and $-170$ km s\textsuperscript{-1}. The absorption in these “C\text{IV}-HVCs” is unlike the absorption due to lower velocity gas tracing the Milky Way disk and halo along the sight line. The C\text{IV}-HVC absorption probably arises in Local Group gas subjected to ionizing extragalactic background radiation.
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Figure 2. Photoionization model calculation for the $-283$ km s$^{-1}$ C$\text{iv}$-HVC toward Mrk 509. The points indicate the model predictions of the ionic column densities as a function of ionization parameter, $\Gamma (= n_e/n_H)$. Solid lines indicate the portions of the ion curves that satisfy the observational constraints. The vertical line indicates the value of $\log \Gamma = -2.55$ (or $\log n_H = -3.82$) that allows a simultaneous fit to all the observable constraints. The dashed line is a prediction for O VI. The physical parameters of the model are listed in Table 1.

Simulations of large-scale structure formation involving gas hydrodynamics, Ly$\alpha$ clouds at $2 < z < 4$ with $10^{14} < N(\text{H}I) < 10^{17}$ cm$^{-2}$ trace the diffuse gas in the filamentary and sheet-like structures that surround and connect galaxies (Zhang et al. 1995; Petitjean et al. 1995; Hernquist et al. 1996; Miralda-Escudé et al. 1996). The simulations indicate that the gas in the sheets and filaments gradually become denser concentrations that eventually form galaxies. Some of this gas may have survived to the present day. The C$\text{iv}$-HVCs and some of the $\text{H}i$-HVCs may be manifestations of such filamentary structures within the nearby universe. Additional observations of C$\text{iv}$-HVCs along other sight lines would provide important insight into the viability of this hypothesis.

The origins of HVCs have been debated for decades. The C$\text{iv}$-HVCs provide fundamentally new, and challenging, information that has not been available previously. While the C$\text{iv}$-HVCs trace mainly ionized gas, their study has applications for understanding neutral HVCs as well. We detect weak $\text{H}i$ emission within $2^\circ$ of the Mrk 509 sight line. The physical connection between the C$\text{iv}$-HVCs and the $\text{H}i$-HVCs is still uncertain, though the relative proximity of the $\text{H}i$-HVCs and the velocity similarities of the $\text{H}i$-HVCs to the C$\text{iv}$-HVCs along the sight line suggests that the two types of HVCs are related. The simplest relationship would be one in which the C$\text{iv}$-HVCs trace the extended, ionized, low density regions of the $\text{H}i$-HVCs.
4. Where Do We Go From Here?

There are several observations that could provide further insight into the nature of the C\text{IV}-HVCs.

4.1. H\textalpha{} Emission

Considerations of different scenarios for the production of H\textalpha{} emission (Ferrara & Field 1994; Bland-Hawthorn et al. 1995; Bland-Hawthorn 1997) illustrate that it can be a powerful discriminator between an extragalactic and a Galactic location for the C\text{IV}-HVCs. The C\text{IV}-HVCs should have very low levels of H\textalpha{} emission if the clouds are extragalactic entities photoionized by extragalactic background radiation. If, however, the clouds are local (i.e., in the Milky Way halo), H\textalpha{} emission due to photoionization by starlight or collisional ionization produced by shocks would be strong and readily detectable ($I_{H\alpha} > 10$ mR). H\textalpha{} emission with an intensity $I_{H\alpha} \sim 100$ mR is observed in many directions toward HVCs that are known to be located within 10 kpc of the Galactic plane (Tuft, Reynolds, & Haffner 1998). Detectable line emission from gas as far away as the Magellanic Stream may be due to photoionization by photons escaping the Galaxy (Bland-Hawthorn & Maloney 1998).

4.2. O\textvi{} Absorption

The best diagnostic of hot, collisionally ionized gas at ultraviolet wavelengths is the O\textvi{} doublet at 1031.93, 1037.62 Å. The energy required to convert O\textve{} into O\textvi{} is 114 eV, well above the He\textii{} absorption edge at 54 eV and the ionization potential of C\textiii{} at 48 eV. A plasma that is radiatively cooling from $\sim 10^6$ K should have $N(\text{O\textvi{}})/N(\text{C\textiv{}}) \sim 1–10$ (Benjamin & Shapiro 1999). Models for conductive interfaces (Borkowski, Balbus, & Fristrom 1990) and evolved supernova remnants (Slavin & Cox 1992; Shelton 1998) yield similar ratios. If the C\text{IV}-HVCs are extragalactic clouds photoionized by background radiation, then the amount of O\textvi{} in the clouds should be roughly 1–2 orders of magnitude less than C\text{IV} in the absence of collisional processes.

We will be able to search for O\textvi{} associated with the C\text{IV}-HVCs with the Far Ultraviolet Spectroscopic Explorer (see Sembach, this volume). A column density $N(\text{O\textvi{}}) = 6.5 \times 10^{12}$ cm$^{-2}$ will have an equivalent width of $\approx 8$ mÅ, which is roughly the detection limit for S/N$\approx 30$ per FUSE resolution element for an O\textvi{} line with a thermal broadening in $2 \times 10^4$ K gas ($b = 4.6$ km s$^{-1}$).

It is interesting to note in this context that Cen & Ostriker (1998) have recently proposed that as much as 50% of the baryons in the nearby universe may be in the form of hot ($T \sim 10^5-10^7$ K) gas. Thus, a test for the presence of O\textvi{} in the C\text{IV}-HVCs could also place constraints on the amount of gas that exists in intergalactic clouds at temperatures of $10^5-10^6$ K.

4.3. HST Data for Other Sight Lines

Sembach et al. (1999) identified two HVCs toward PKS 2155-304 ($l = 17.7^\circ$, $b = -52.2^\circ$) that appear to have properties similar to those of the C\text{IV}-HVCs toward Mrk 509. The clouds show C\text{IV} absorption with little Si\textii{} absorption. The velocities are lower than those of the Mrk 509 C\text{IV}-HVCs ($\approx -256$ and $-140$ km s$^{-1}$), but are consistent with an extragalactic location. There is no detectable 21 cm
emission at these velocities directly along the sight line, but mapping of the sky
nearby reveals low column density HI-HVCs similar to those near the Mrk 509
sight line. Further ultraviolet observations of the C iv-HVCs toward PKS 2155-
304 with the HST would allow stronger constraints to be placed on their ioniza-
tion conditions. Identification and investigation of additional C iv-HVCs along
other sight lines would help constrain the typical kinematical properties and
covering factors of the clouds, which could then be compared to those for higher
redshift absorption systems.

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