The Discovery and Origin of a Very High-velocity Cloud Toward M33

Y. Zheng1, J. K. Werk2, J. E. G. Peek3, and M. E. Putman1

1 Department of Astronomy, Columbia University, New York, NY 10027, USA; yzheng@astro.columbia.edu
2 Department of Astronomy, University of Washington, Seattle, WA 98195, USA
3 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

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Abstract

We report the detection of a largely ionized very high-velocity cloud (VHVC; \(v_{\text{LSR}} \sim -350\) km s\(^{-1}\)) toward M33 with the Hubble Space Telescope/Cosmic Origin Spectrograph. The VHVC is detected in O I, C II, Si II, and Si III absorption along five sightlines separated by \(\Delta \sim 0^\circ 06-0^\circ 4\). On sub-degree scales, the velocities and ion column densities of the VHVC remain relatively constant with standard deviations of \(\pm 14\) km s\(^{-1}\) and \(\pm 0.15\) dex between the sightlines, respectively. The VHVC has a metallicity of \([\text{O I}/\text{H I}] = -0.56 \pm 0.17\) dex (\(Z = 0.28 \pm 0.11\) Z\(_{\odot}\)). Despite the position–velocity proximity of the VHVC to the ionized Magellanic Stream, the VHVC’s higher metallicity makes it unlikely to be associated with the Stream, highlighting the complex velocity structure of this region of sky. We investigate the VHVC’s possible origin by revisiting its surrounding H I environment. We find that the VHVC may be (1) a MW CGM cloud, (2) related to a nearby H I VHVC—Wright’s Cloud, or (3) connected to M33’s northern warp. Furthermore, the VHVC could be a bridge connecting Wright’s Cloud and M33’s northern warp, which would make it a Magellanic-like structure in the halo of M33.

Key words: galaxies: individual (M33) – galaxies: halos – intergalactic medium

1. Introduction

The inner halo (\(\lesssim 20\) kpc) of the Milky Way (MW) is populated by neutral H I high-velocity clouds (HVCs) and their ionized counterparts (ionized HVCs). HVCs are usually defined to have velocities of \(|v_{\text{LSR}}| > 90\) km s\(^{-1}\), where \(v_{\text{LSR}}\) is the velocity in the rest frame of the local standard of rest (LSR) with respect to the Sun. The neutral and ionized HVCs exist at an interface where outflows from the Galactic disk is likely to be closely interacting with inflows from the halo (see Putman et al. 2012 and references therein). HVCs are commonly arranged in large complexes observed in H I 21 cm emission (Wakker & van Woerden 1991); on the other hand, ionized HVCs are detected via optical or ultraviolet (UV) absorption lines toward background stars or quasars (see van Woerden & Wakker 2004 and references therein). The metallicities of HVCs vary from \(\sim 0.1\) solar (e.g., complex A, WD), to \(\sim 0.1–0.3\) solar (e.g., complex C; Tripp et al. 2003; Shull et al. 2011) and likely near solar (e.g., complex M, WB), complicating the interpretation of the origins (van Woerden & Wakker 2004). Distances to HVCs are difficult to obtain; the only direct means is to bracket the distance via the detection (non-detection) of absorption lines at similar velocities toward background (foreground) stars projected along the line of sight to the clouds (e.g., Thom et al. 2006, 2008; Lehner & Howk 2010; Smoker et al. 2011; Peek et al. 2016). So far, it is generally suggested that most of the clouds lie within 5–15 kpc of the Sun (e.g., Wakker 2001; Wakker et al. 2008; Lehner et al. 2012).

One H I complex that does not lie in MW’s inner halo is the Magellanic Stream, a \(\sim 200^\circ\) long H I structure that originates from the Magellanic Clouds (MCs; Putman et al. 2003; Nidever et al. 2008, 2010). The Stream has been stripped from the MCs by tides and/or ram pressure forces as the two galaxies move through the MW halo (e.g., Murai & Fujimoto 1980; Gardiner et al. 1994; Besla et al. 2010). The closest distance of the Stream is likely \(\sim 55\) kpc near the MCs, while the most distant point is suggested to be at \(\sim 100\) kpc near the tail based on tidal models (Besla et al. 2012) and geometrodynamical calculation (Jin & Lynden-Bell 2008). Except for very close to the MCs, the metallicity of the Stream is \(\sim 0.1\) solar, measured from several QSO sightlines that pass through different locations of the Stream (Gibson et al. 2000; Fox et al. 2010, 2013; Richter et al. 2013). Near the Stream, numerous small individual H I HVCs are found moving at Magellanic-like velocities (Braun & Thilker 2004; Brüns et al. 2005; Stanimirović et al. 2008; Nidever et al. 2010). In addition, Fox et al. (2014, hereafter F14) found that the Magellanic System, including the Stream, the Bridge, and the Leading Arm, is likely to be surrounded by an ionized extended envelope with a cross-section of \(\approx 11,000\) deg\(^2\), which is nearly four times larger that its H I-bright region. Excluding the MCs themselves, the Magellanic H I-bright regions\(^4\) have a total mass of \(M(\text{H I} + \text{H II}) \sim 1.4 \times 10^8 (d/55\) kpc\(^2\) \(M_\odot\) (Brüns et al. 2005; F14), and its ionized envelope beyond the main body has an ionized mass of \(M(\text{H II}) \sim 5.5 \times 10^8 (d/55\) kpc\(^2\) \(M_\odot\) (F14).

On the projected sky, the ionized envelope of the Magellanic Stream near its tip may overlap with M31’s and M33’s circumgalactic medium (CGM), seen toward extragalactic sources (e.g., quasars; QSOs) and in emission, complicating the interpretation of the gas velocities in this region (F14; Nidever et al. 2010; Lehner et al. 2015). The tip of the Stream and its surrounding H I clouds move at \(\sim 500 \lesssim v_{\text{LSR}} \lesssim 300\) km s\(^{-1}\) (F14; Nidever et al. 2010; Lehner et al. 2015). Because M31’s and M33’s systemic velocities are \(\sim 301\) km s\(^{-1}\) (Courteau & van den Bergh 1999) and \(\sim 179\) km s\(^{-1}\) (Corbelli & Schneider 1997), respectively, it is possible that the CGM of these two galaxies may have velocities comparable to the Magellanic Stream (Lockman et al. 2012; Lehner et al. 2015; Wolfe et al. 2016). In addition, this region is close to the area studied in Richter et al. (2016), who suggested that nearby

\(^4\) Including the Magellanic Stream, the Magellanic Bridge, and the Leading Arm; see F14.
absorbers are likely to be streaming toward the Local Group center. To intensify the intrigue of this Magellanic-M33-M31 overlap region, here we report the detection of a VHVC along five sightlines toward M33, and therefore the VHVC lies in front of M33’s disk. As shown in Figure 1, between M33 and MW, there are five possibilities that may cause the absorption: (A) an MW CGM cloud, (B) the ionized envelope of the Magellanic Stream, (C) an M31 CGM cloud, (D) M33’s northern warp, and (E) M33’s outflow. In addition, on the projected sky the VHVC is ~2° from an H II-VHVC—Wright’s Cloud (Wright 1974, 1979, hereafter, W79) and they are at similar velocities. The distance to Wright’s Cloud is not yet clear; we discuss the relation of the VHVC and Wright’s Cloud and the implication in Section 5.5.

In the following sections, we present our data and discuss the origin possibilities of the VHVC and its possible connections with nearby H I structures. In Section 2 we show absorption-line data obtained from HST/COS, and H I 21 cm data from the Arecibo Galaxy Environment Survey (AGES; Keenan et al. 2016) and the Galactic Arecibo L-band Feed Array H I survey (GALFA-H I; Peek et al. 2011). In Section 3, we calculate the O I abundance and show the gas properties over sub-degree scale for the VHVC. In Section 4, we discuss the inferences that can be drawn from the metallicity and the spatial patchiness of the VHVC in relation to the Magellanic Stream (Case B in Figure 1). We discuss the possible origins (Case A, C, D, and E in Figure 1) of the VHVC in Section 5, and summarize our findings in Section 6.

2. Data and Measurement

2.1. HST/COS Observations

The VHVC is a serendipitous detection in the observations described in Zheng et al. (2017, hereafter Z17). Among the seven sightlines (S1–S7) that were used in Z17, five show significant ion absorption lines at $v_{\text{LSR}} \sim -350$ km s$^{-1}$, while the other two are heavily contaminated by stellar lines and/or M33’s interstellar absorption lines at the corresponding velocities. Therefore, in this work, we only use the five sightlines, which are M33-UIT-236, M33-FUV-350, M33-FUV-444, NGC 592, and M33-FUV-016. Hereafter, we use their sightline ID S1, S2, S3, S4, S7, the same as those in Z17 for consistency.

The VHVC is detected in absorption lines of $^5$ O I $\lambda\lambda$302, C II $\lambda\lambda$1334, Si II $\lambda\lambda$ 1190, 1193, and Si III $\lambda\lambda$1206. Hereafter, we refer to these ions as “low ions” because they represent low-ionization states that require <20 eV to be produced. We do not detect Fe II, Si II, P II, Si IV absorption lines at similar velocities, even though our data cover these ionic species; the lack of these ions may reflect some limits on metallicity and ionization condition, which we decide not to explore further since it requires sophisticated ionization assumptions and modeling.

The HST/COS observations have been thoroughly described in Z17; here, we briefly summarize relevant details. The spectra were obtained using the G130M FUV grating with a central wavelength of 1291 Å and a wavelength coverage of 1134–1431 Å. The velocity resolution at full width of half maximum (FWHM) is 14–19 km s$^{-1}$ per resolution element (COS data handbook; Fox 2015). The spectra were taken with the Primary Science Aperature, which has an aperture size of 2.5 arcsec. We retrieved the calibrated and co-added data from the Mikulski Archive from Space Telescopes (MAST). The spectra have been processed by the standard CalCOS pipeline (version 3.0). In Z17, we have justified the CalCOS products are reliable for our scientific analysis, mainly benefiting from

5 We do not use Si II $\lambda$ 1260 Å because it is blended with S II $\lambda$ 1259 Å absorption from M33 (see Z17).
6 Si II/Si III/C II need 8.15/16.35/11.26 eV to be ionized from their previous states, respectively.
Among the detected ionic absorption lines, those of O I λ1302 Å require special treatment. From the original CalCOS co-added spectra, we find a clear O I absorption line along S7. The other four spectra are dominated by strong airglow emission at the expected velocities due to O I in the exosphere of the Earth. To confirm the S7 detection and to check if other sightlines also show similar O I signals, we conducted night-only data reduction following the night-only calibration tutorial7 provided by Justin Ely. Briefly, we installed the CalCOS v3.0 pipeline locally and retrieved new calibration reference files using the HST Calibration Reference Data System. We used the TimeFilter Python module to select the night-only photons from the raw data, then constructed the O I night-only spectra for the five sightlines. From the night-only spectra, we find that S7 presents the same O I λ1302 absorption as seen in the original spectrum but with a noisier profile due to the reduced number of photons. However, S1–S4 still do not show O I absorption, which is most likely due to the low signal-to-noise ratio (S/N) of the night-only spectra.

With the reduced spectra, we perform continuum and Voigt-profile fitting following the procedures outlined in Z17. Briefly, for singular transition we normalize the absorption profile by fitting stellar continuum and stellar lines with Legendre polynomials within ±1000 km s\(^{-1}\) from the line center. The fitting is evaluated using the reduced \(\chi^2\) values. For the Voigt-profile fitting, we fit one component for each line unless obvious multiple components exist. The Voigt-profile fits give estimates for the centroid velocity \(v\), Doppler width \(b\), and column density \(N_{\text{col}}\), and the fitting is performed multiple times iteratively so that these parameters converge. In Figure 2, we show the O I, C II, Si II, and Si III absorption lines that have been continuum-normalized and Voigt-profile fitted, and in Table 1 we tabulate the best-fit \(v\), log \(N\), and FWHM (\(\approx 1.667b\)). Overall, all lines yield straightforward solutions, except those detected along S2, which has considerable larger uncertainties due to the blending with M33’s interstellar absorption at less negative velocities. In addition, for O I absorption lines in Figure 2, we use the night-only spectra for S1–S4 because their original spectra at \(v_{\text{LSR}} \sim -350\) km s\(^{-1}\) are dominated by geocoronal airglow emission. For S7, we use the original CalCOS co-added spectrum because the absorption is isolated from the airglow emission at \(v_{\text{LSR}} > -200\) km s\(^{-1}\) and this spectrum has a higher S/N than the night-only spectrum.

### 2.2. H I 21 cm data

The H I 21 cm spectra shown in the top row of Figure 2 are from the AGES (Keenan et al. 2016). AGES data have an angular resolution of \(\sim 4'\), spectral resolution of \(\sim 5.2\) km s\(^{-1}\), and a 1σ sensitivity of \(\sim 1.5 \times 10^{17}\) cm\(^{-2}\) over 10 km s\(^{-1}\). Only S2 and S7 indicate >2σ emission signals, which we fit with Gaussian components. S1, S3, and S4 do not show significant detection above the noise level, thus we integrate the spectra from \(-400\) to \(-300\) km s\(^{-1}\) to derive a 3σ upper limit. Note that this \([-400, -300]\) km s\(^{-1}\) integration range is relatively broad as compared with the narrow H I lines detected in S2 and S7; the derived 3σ upper limits should be conservative estimates for the H I along S1, S3, and S4. We tabulate the Gaussian-fitted H I velocities and column densities and the integrated upper limits in Table 1; the column density values are calculated using \(N(\text{H I}) = 1.823 \times 10^{18} \int_{-400}^{-300} T_B dv\) cm\(^{-2}\) (Draine 2011). Note that H I-bearing gas may not be entirely co-spatial with the VHVC detected along HST/COS sightlines, as AGES beam size (\(\sim 4'\)) is \(\sim 100\) times larger than

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7 https://justincely.github.io/AAS224/timefilter_tutorial.html

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Figure 2. Top row shows the H I 21 cm spectra from AGES; the red curves are Gaussian fits to the two possible H I detections with >2σ significance. The data have a brightness temperature sensitivity of 4–8 mK (Auld et al. 2006). The bottom four rows show the continuum-normalized O I, C II, Si II, and Si III absorption lines and their Voigt-profile fits (red); the underlying blue curves indicate the overall fits. The absorption components at \(v_{\text{LSR}} \sim -350\) km s\(^{-1}\) are associated with the VHVC, and those at \(-300 < v_{\text{LSR}} < -100\) km s\(^{-1}\) (\(\sim 0\) km s\(^{-1}\)) are from M33 (MW).
From the top panel of Figure 3, we along OHII and SiIII mean and standard deviation. S7, the two components are considered as one while calculating the overall detection a 3σ upper limit is indicated. For S2, we found a 3σ upper limit of |O I/H I| ≤ 0.17 dex and Z ≤ 0.68 Z⊙, consistent with the value estimated from S7.

### 3. Gas Properties of the VHVC

#### 3.1. Metallicity

The O I detection along S7 provides us a direct metallicity measurement for the VHVC without assuming any ionization correction. This is because O I and H I have comparable ionization potentials from their ground states, and O I is not likely to be heavily depleted onto dust (Jenkins 2009). As shown in Table 1, we find log N(O I) = 14.00 ± 0.07 cm⁻² and log N(H I) = 17.87 ± 0.14 cm⁻² for S7. Thus, the gas-phase abundance is 12+log(O/H) = 8.13 ± 0.16. Using the oxygen solar abundance (12+log(O/H))⊙ = 8.69 ± 0.05; Asplund et al. 2009), we measure [O I/H I] = log(O/H) − log(O/H)⊙ = −0.56 ± 0.17 dex, corresponding to a metallicity of Z = 10¹⁰(Ο/H)⊙ = 0.28 ± 0.11 Z⊙ for the VHVC. In addition, sightline S2 shows similar H I emission although O I only has a 3σ upper limit. For S2, we found a 3σ upper limit of |O I/H I| ≤ 0.17 dex and Z ≤ 0.68 Z⊙, consistent with the value estimated from S7.

#### 3.2. Sub-degree Scale Variation

For each ion, we calculate the mean and standard deviation values of v, log N, and FWHM among the five sightlines, which are tabulated in Table 1. Both H I and the four ions show similar mean centroid velocities at vLSR ∼ −350 km s⁻¹ with a standard deviation of ∼15 km s⁻¹. Column densities vary up to 0.15 dex as measured from Si II; in most cases the differences among the sightlines remain <0.1 dex. As for the FWHM, a relatively large standard deviation of 27 km s⁻¹ is seen in Si III, contributed by the blended Si III absorption line along S2. Otherwise the FWHM values of all the transition lines remain <70 km s⁻¹.

The above standard deviations are measured among five sightlines with projected angular separations of ∼0°06–0°14. To determine how the absorption properties fluctuate over this sub-degree scale, we group the five sightlines into pairs and calculate the absolute values of the differences: |log N| − |log N|, and |v| − |v|. From the top panel of Figure 3, we find that the maximum log N difference is ∼0.4 dex with an average of ∼0.15 dex. The bottom panel shows that the centroid velocity differences between sightlines vary up to 30 km s⁻¹ with an average of ∼14 km s⁻¹, which is well within COS velocity resolution. The small sightline-to-sightline variations suggest that the VHVC is relatively smooth on sub-degree scales. To better interpret the smooth distribution, it is necessary to know the physical separations between the five sightlines. We will investigate this in Section 5 where the potential origins of the VHVC are discussed.

### 4. Is the VHVC Related to the Magellanic Stream?

In the vicinity of the Magellanic System, large amounts of ionized gas have been found to move at expected Magellanic...
velocities (F14; Nidever et al. 2008). The expected velocities are defined by extrapolating from the H I velocity fields at certain longitudes in the Magellanic coordinate system. Based on this position–velocity proximity, F14 suggested the nearby ionized gas is physically associated with the Magellanic System, forming an ionized envelope surrounding the System. The ionized envelope has a total mass of $M(H II) \approx 5.5 \times 10^{8}(d/55 \text{ kpc})^2 M_\odot$, contributing ~20% of the total mass to the System (excluding the MCs themselves). It extends $\approx 11,000 \text{ deg}^2$ on the sky, including the region where we find the VHVC, which is $\sim 40^\circ$ from the tip of the Magellanic Stream, as is shown in Figure 4 and Case B in Figure 1 (see also Richter et al. 2016 for a even larger estimate on the cross-section for the Magellanic System). Thus, this close projected distance naturally leads us to examine whether the VHVC originates from the Magellanic Stream.

Our main argument against a Magellanic origin is based on the single metallicity we measured from the COS spectrum of S7. The VHVC has a metallicity of $[O/\text{H I}] = -0.56 \pm 0.17$ dex ($Z = 0.28 \pm 0.11 \ Z_\odot$; see Section 3.1). As for the Magellanic Stream, its metallicity has been measured at four locations (see Figure 4). Richter et al. (2013) found that the Stream close to the MCs has $[S/\text{H I}] = -0.30 \pm 0.04$ (0.50 $Z_\odot$; see also Gibson et al. 2000) toward Fairall 9. This material is likely to be recently stripped metal-rich gas that originated from the LMC. Except at the Fairall 9 position, the main body of the Stream has a mean metallicity of $[X/\text{H}] = -1.12$ dex, as calculated at three other positions: $[S/\text{H I}] = -1.13 \pm 0.16$ ($\sim 0.07 \ Z_\odot$) toward RBS 144 (Fox et al. 2013), $[O/\text{H I}] = -1.24 \pm 0.20$ ($\sim 0.06 \ Z_\odot$) toward NGC 7714 (Fox et al. 2013), and $[O/\text{H I}] = -1.00 \pm 0.13$ ($\sim 0.10 \ Z_\odot$) toward NGC 7469 (Fox et al. 2010). Therefore, the metallicity of the VHVC is at least 0.56 dex (3.3σ) higher than the mean metallicity of the Magellanic Stream. In particular, it is 0.68 dex (4σ) higher than the metallicity measured at the tip of the Magellanic Stream toward NGC 7714, which is the closest point to the VHVC in projection (see Figure 4).

We also compare the ion column densities of the VHVC with those of the nearby ionized gas that is presumably associated with the Magellanic Stream. The top panel of Figure 5 shows the $v_{\text{LSR}}$ velocities of Magellanic-related ionized absorbers found in F14. This velocity map shows that the ionized gas, regardless of their origins, move at similar velocities in this region. The potential diversity of gas origins can be seen in the middle and bottom panels. In the middle panel, we show the log $N(\text{Si III})$ values for the ionized gas; the majority of the Magellanic ionized stream near the tip has log $N(\text{Si III}) \gtrsim 13.0$ dex, which is $\sim$0.3 dex lower than that of the VHVC (log $N(\text{Si III}) \sim 13.3$ dex). This difference is shown more obviously when we plot the log $N(\text{Si III})$ values against Magellanic latitude. The VHVC’s column density is $\gtrsim 0.5$ dex higher than those of the Magellanic Stream at similar latitude. Similar trends can also be found in Si II and C II. The ionized envelope of the Magellanic Stream tends to become more and more diffuse at further distances from its H I-bright main body. The VHVC, with higher ion column densities, is unlikely to be associated with the Stream.

We conclude that the VHVC is unlikely to originate from the Magellanic Stream. Near our VHVC, there is an H I-VHVC—Wright’s Cloud—moving at a similar Magellanic velocity. Some authors have suggested Wright’s Cloud may be related to the Magellanic Stream due to their proximity in position–velocity space (W79; Braun & Thilker 2004; Putman et al. 2009; Nidever et al. 2010). Indeed, F14 included Wright’s Cloud as one of the H I-bright regions of the Magellanic System, thus extended the Magellanic ionized envelope 30$^\circ$ beyond Wright’s Cloud (see Figure 1 in F14). However, as we discuss in Section 5.5, Wright’s Cloud’s origin is unclear due to its unknown distance. Therefore, we cast doubt on the existence of the Magellanic ionized envelope within 30$^\circ$ of Wright’s Cloud where there is no other Magellanic-associated H I emission or QSO absorbers. The highly uncertain origin of Wrights Cloud and the evidence that the VHVC is not part of the Stream together suggest that the ionized envelope of the Magellanic Stream may not extend to cover the region of the sky in the direction of M33.
5. The Origin of the VHVC

In this section, we discuss the multiple possibilities for the origin of the VHVC given the complex velocity field on this projected sky. Apart from the Magellanic scenario (Case B) that we argue against in the previous section, there are four other plausible scenarios that could cause the absorption, which we illustrate in Figure 1 as A: a MW CGM cloud, C: an M31 CGM cloud, D: M33’s northern warp, and E: M33’s outflow. Here, we evaluate each of these possibilities separately.

5.1. A MW CGM Cloud?

As we annotate as Case A in Figure 1, the VHVC could be a cloud at an unknown distance in MW’s CGM. Though we have shown in Section 4 that the VHVC is unlikely to be part of the Stream, it could be closer in the MW’s inner halo similar to other MW HVCs. The $\sim 0.3 \; Z_{\odot}$ metallicity of the VHVC makes it similar to some H I complexes, such as Complex C ($Z = 0.1 - 0.3 \; Z_{\odot}$; Tripp et al. 2003; Shull et al. 2011). In Figure 6, we compare the column density (log $N$) variations of the VHVC with those MW HVCs detected in Si III between 58 QSO sightlines with angular separation of $\leq 30^\circ$ (Collins et al. 2009). The larger variations of the MW HVCs still hold when we separate Collins et al. sample by positive/negative HVC velocities and by northern/southern QSO sightlines.

We note that the direct comparison in angular separation between our VHVC and the MW HVCs may not be informative because it does not reflect the actual physical separations of the paired sightlines on the sky. The MW HVCs are generally at distances of 5-15 kpc from the Sun (Wakker 2001; Wakker et al. 2008; Lehner et al. 2012); we assume them at $d = 10$ kpc and find physical separations of $\leq 5$ kpc for these MW paired sightlines as shown in the bottom panel of Figure 6. To make our VHVC’s physical scale comparable to those of the MW HVCs, we find its distance would have to be $\sim 840$ kpc, which is beyond the virial radius of the Galaxy and is as far as M33. Therefore, our sightlines toward the VHVC should probe a smoother medium on sub-degree scales than those in Collins et al. (2009) if it belongs to the MW’s CGM. However, if the VHVC is instead associated with M33 as we discuss in Sections 5.3 and 5.4, the smoother column density variation in the bottom panel suggests that the VHVC is unlikely to represent HVC-like features in M33’s CGM, assuming that M33 has similar HVC population as MW.
5.2. An M31 CGM Cloud?

The VHVC moves at $v_{\text{LSR}} \sim -350$ km s$^{-1}$ while M31’s systemic velocity is $v_{\text{LSR}} = -301$ km s$^{-1}$ (Courteau & van den Bergh 1999). If put at M31’s distance, the VHVC would be ~200 kpc from the galaxy in projection. We show this possibility as Case C in Figure 1. By comparing the ion column densities of the VHVC with those detected in M31’s CGM by Lehner et al. (2015), we find that the VHVC generally has higher C II, Si II, and Si III column densities. Beyond 50 kpc of M31’s CGM, Lehner et al. (2015) reported no significant detection of Si II with an upper limits of $\log N(\text{Si II}) \lesssim 13.19$. In addition, Si III absorption lines were detected along four sightlines with $\langle \log N(\text{Si III}) \rangle = 12.53$, while C II column densities are mostly upper limits ($\log N(\text{C II}) < 13.70$) with only one detection at $\log N(\text{C II}) = 13.16$. These measurements indicate that the ionized gas in the outskirts of M31’s CGM is likely to be diffuse, with column densities lower than those we measured for the VHVC: $\langle \log N(\text{C II}) \rangle = 13.29$, $\langle \log N(\text{Si III}) \rangle = 13.27$, and $\langle \log N(\text{C II}) \rangle = 14.13$. Given the column density mismatch, we disfavor an origin of the VHVC being part of M31’s CGM. Note that M31’s CGM may be patchy, similar to the cool CGM of $L^*$ galaxies in the COS-Halos survey (Werk et al. 2013); however, the chance of our sightlines intercepting a very high-density clump at large distance from the host galaxy is rare. Future work on the patchiness of M31’s CGM and those of $L^*$ galaxies may help to confirm or dispute our argument for no association between the VHVC and M31.

5.3. An M33 CGM Cloud or an M33 Outflow?

M33 has a systemic velocity of $v_{\text{LSR}} \sim -180$ km s$^{-1}$ (Corbelli & Schneider 1997), therefore the VHVC would be moving at $\delta v \sim -170$ km s$^{-1}$ in the galaxy’s rest frame. If we simplify M33’s gravitational potential as a point mass $\sim 5.5 \times 10^{10} M_\odot$ (dark matter+baryon; Corbelli 2003), the VHVC should be within $\sim 16$ kpc of the galaxy to remain gravitationally bound. This calculation certainly omits the complex mechanisms (ionization, cooling, equilibrium, etc.) that regulate clouds’ survivability in a galaxy’s CGM; however, it hints that the VHVC is most likely to be near M33’s disk if it has some M33 origins. Observationally, the COS-Halos survey (Werk et al. 2013) found that most of the CGM clouds of $L \sim L^*$ galaxies at $z \sim 0.2$ were within $\sim 100$ km s$^{-1}$ of their host galaxies’ systemic velocities and only a few exceed 200 km s$^{-1}$. Therefore, it is unlikely that our VHVC is a CGM cloud of M33 at large radius given its high velocity. As for the possibility that the VHVC exists in the vicinity of M33’s disk, we have shown in Section 5.1 that the VHVC is unlikely to be HVC-like features due to its smooth column density distribution. In the following, we consider two other near-the-disk scenarios: (1) the VHVC represents an outflow from M33 (Case E in Figure 1), which we discuss in the rest of this section; (2) the VHVC could be an ionized extension of M33’s northern warp (Case D in Figure 1; see Section 5.4).

The VHVC should lie in front of M33’s disk because our background targets are UV-bright stars in M33. If we use these M33 stars as the reference points, the VHVC is moving at $\sim [-180, -100]$ km s$^{-1}$. These negative velocities with respect to M33 indicate that the VHVC could be regional outflows from the disk but remain in the vicinity of the disk; the outflows could be driven by stellar winds or supernova feedback (Case E in Figure 1)—outflows powered by an active galactic nuclei are not considered—as M33 does not host a massive central black hole (Merritt et al. 2001). In the following, we evaluate the possibility of outflow by comparing the ion properties of the VHVC with those of galactic outflows seen in absorption in other galaxies.

First, we find that our COS spectra do not show a detection of Fe II—an ion that is commonly reported in galactic outflow observations of both nearby (e.g., LMC; Lehner et al. 2009) and $z \sim 1$ star-forming galaxies (Martin et al. 2012; Rubin et al. 2010, 2014). The non-detection is unlikely to be due to the sensitivity limit of our COS spectra, which is sensitive to Fe II absorption lines with $\log N(\text{Fe II}) \gtrsim 13.5$. If M33 indeed has an outflow similar to those in nearby and $z \sim 1$ galaxies (e.g., Martin et al. 2012; Rubin et al. 2014), the Fe II column densities should be $\log N(\text{Fe II}) \gtrsim 14.0$, well above our sensitivity limit.

Second, we investigate the possibility based on ion absorption line widths and profile shapes. Galactic outflows have been detected in several different ions, such as Na I, Mg II, and Fe II with broad absorption lines (FWHM $\gtrsim 100$ km s$^{-1}$; Heckman et al. 2000; Martin 2005; Martin et al. 2012; Weiner et al. 2009; Chen et al. 2010; Rubin et al. 2010, 2014). Recently, Chisholm et al. (2016, hereafter C16) studied Si II/Si III-tracing outflows in 37 nearby star-forming galaxies observed with HST/COS G130M. They generalized that galactic outflows detected in Si II and Si III commonly have FWHM values of $\sim 230–500$ km s$^{-1}$ and the outflows’ line profiles tend to exhibit more extended, gradually shallowing blue absorption edges compared with the red edges. This profile asymmetry may be explained by outflows being continuously accelerated with more diffuse gas columns at larger distances. Because our spectra were observed with the same instrument, we can directly compare our Si II/Si III measurements with C16. As we show in Section 3.2, except Si II that is blended with absorption from M33, the absorption lines of the VHVC have a mean FWHM $\lesssim 70$ km s$^{-1}$, which is at least a factor of 3 narrower than those of galactic outflows reported by C16. In addition, our absorption-line profiles are mostly symmetric relative to the line centroids as are shown in Figure 2. We note that the 37 galaxies in C16 span distances of $3–880$ Mpc, corresponding to COS aperture physical sizes of 0.04–11 kpc. Within this dynamical range C16 found no correlation between the COS aperture physical sizes and galactic wind line widths. Therefore, although the physical COS aperture size in our observation ($\sim 0.01$ kpc) is smaller, this difference is not likely to cause the distinct line widths and line profile shapes. We conclude that the VHVC is unlikely to represent an outflow from M33’s disk.

5.4. M33’s Extended Warp Material?

The northern warp of M33 moves at negative velocities of $v_{\text{LSR}} \sim [-300, -200]$ km s$^{-1}$ (Putman et al. 2009; Corbelli & Schneider 1997), which is close to the velocity of the VHVC. Although the northern warp’s orientation is unclear, it is possible that the warp folds toward the MW and cause the ionized gas absorption along our line of sight (see Case D in Figure 1). That M33’s northern warp may have a diffuse extension is hinted by the deeper H I maps shown in Putman et al. (2009; Figures 3 and 7) and in Keenan et al. (2016; Figure 1), which both detected some diffuse H I emission at $v_{\text{LSR}} \lesssim -250$ km s$^{-1}$ near the warp. In particular, Putman et al. (2009) suggested the diffuse
H I structures cannot be reproduced in M33’s tilted-ring model (Corbelli & Schneider 1997) and an additional component is in need to explain these features.

To examine the possible connection between the VHVC and the northern warp, in Figure 7 we show the position–velocity map of M33’s H I disk and warp projected along its major axis. The major axis is defined based on M33’s central optical disk with a position angle (PA) \(-21^\circ\) as adopted in Corbelli & Schneider (1997). We show the relative positions of M33’s warp and central disk in contours in Figure 8, along with a straight line indicating its major axis. To generate the position–velocity map in Figure 7, we project all the H I signals within 26° > R.A. > 21° and 28.6° < decl. < 32° along M33’s major axis and compute the mean \(T_b\). From Figure 7, we find that the VHVC could be potentially associated with M33’s northern warp as revealed by their proximity in the position–velocity space.

If the VHVC is part of M33’s northern warp, then the warp folds toward the MW and is stable as inferred from the smooth column density and velocity distributions of the VHVC (Figure 6). In addition, the VHVC’s metallicity of [O i/H i] = \(-0.56 \pm 0.17\) dex implies that the warp has a similar oxygen abundance to M33’s ISM ([O i/H i] = \(-0.42 \pm 0.06\) dex; Crockett et al. 2006). This similarity rules out the possibility that M33’s warp represents the accretion of primordial H I from outside of the disk. Instead, it favors the scenario that M33 closely interacted with M31 in the past which resulted in a distorted gaseous warp (Putman et al. 2009) and stellar disk (McConnachie et al. 2009). This contradicts a recent dynamical study of M33’s orbit history (Patel et al. 2017) that suggests a rare chance (<1%) at 4\(\sigma\) of an M33-M31 close encounter in the past.

5.5. Wright’s Cloud Association?

Wright’s Cloud is composed of north–south and east–west arms as shown in Figure 8. It is \(\sim 2^\circ\) from our VHVC and moves at \(v_{\text{LSR}} \sim [-450, -330] \text{ km s}^{-1}\), similar to our VHVC. These two clouds’ similar velocities and close angular distance suggest a potential connection. In the bottom position–velocity panel, Wright’s Cloud can be found with several noticeable H I concentrations at R.A. \(\sim 17^\circ - 22^\circ\). The VHVC is represented by its H I emission and Si II absorption at R.A. \(\sim 23^\circ\), generally following the velocity gradient of Wright’s Cloud.

The distance to Wright’s Cloud is unknown. Some authors have indicated that Wright’s Cloud could be part of the Magellanic Stream based on position–velocity proximity (e.g., W79; Braun & Thilker 2004; Putman et al. 2009; Nidever et al. 2010). However, if the VHVC is related to Wright’s Cloud, its metallicity of \(Z = 0.28 Z_\odot\) (Section 3.1) implies that Wright’s Cloud, together with the VHVC, is unlikely to be related to the Magellanic Stream.
If the VHVC is part of Wright’s Cloud, then Wright’s Cloud could be a nearby H I feature in the MW’s inner halo (see Section 5.1). On the other hand, if we combine Figures 7 and 8, there is a possibility that our VHVC is forming an ionized bridge that connects Wright’s Cloud and M33’s northern warp. If Wright’s Cloud is in M33’s CGM, it would contain a total mass of \( M(H) \approx 4.8 \times 10^8 M_\odot (d/840 \text{ kpc})^2 \) as calculated using GALFA-H I data (see also W79; Braun & Thilker 2004). Wright’s Cloud would be \( \approx 70 \text{ kpc} \) wide in size and \( \approx 10 \text{ kpc} \) at its nearest point to M33 if put at the galaxy’s distance, as have been pointed out in W79. In such case, Wright’s Cloud would be a Magellanic-like H I complex in M33’s CGM.

With an estimated H I mass of \( \approx 10^8 M_\odot \) at the distance of M33, Wright’s Cloud may then have an optical counterpart. However, there is no obvious optical counterpart in Wright’s Cloud in the Pan-STARRS1 database (Bernard et al. 2016; Chambers et al. 2016). In addition, we briefly search the GALEX map and Planck dust map (Planck Collaboration et al. 2016) on the MAST archive but do not find any UV or dust emission excess. If Wright’s Cloud does not have an optical counterpart, it is an outlier from those H I sources (\( M_\text{HI} \gtrsim 10^7 M_\odot \)) found in Pisano et al. (2007, 2012) which have stellar components. It is more likely to be similar to the Magellanic Stream or other H I features surrounding galaxies as noted by Sancisi et al. (2008; and references therein).

6. Conclusion

We report the detection of a VHVC in direction of M33. The detection was made along five HST/COS sightlines targeted at UV-bright stars in M33’s disk. The VHVC was found in O I, C II, Si II, and Si III absorption lines at \( \nu_{\text{LSR}} \sim -350 \pm 15 \text{ km s}^{-1} \). We do not find Fe II, P II, S II, or Si IV absorption at similar velocities even though our COS spectra cover these ionic species. The mean ion column densities of the VHVC are \( \log (N(O I)) = 14.00 \pm 0.07, \log (N(C II)) = 14.13 \pm 0.08, \log (N(Si II)) = 13.29 \pm 0.15, \) and \( \log (N(Si III)) = 13.27 \pm 0.11 \).

We measure a metallicity \( [O I/H I] = -0.56 \pm 0.17 \) \( (Z = 0.28 \pm 0.11 Z_\odot) \) for the VHVC, which is 0.68 dex \((4\sigma)\) higher than the metallicity found for the tip of the Magellanic Stream. The higher metallicity and stronger C II, Si II, and Si III absorption suggest that the VHVC is most likely not associated with the Magellanic Stream. Furthermore, this lack of association may signify that the ionized envelope of the Magellanic Stream is less extended than previously reported in the direction toward M33.

We find that the VHVC is unlikely to be related to M31’s CGM since it would be \( \approx 200 \text{ kpc} \) from M31’s disk in projection but its ionic lines are much stronger than those detected beyond 50 kpc of M31’s disk. We also rule out the possibility that the VHVC resides in M33’s CGM at large radius given its high velocity \((6\upsilon \sim -170 \text{ km s}^{-1})\) with respect to M33’s systemic velocity. If the VHVC has some M33 origins, it has to be within \( \approx 16 \text{ kpc} \) from the galaxy to remain gravitationally bound. In the vicinity of M33’s disk, we find that the VHVC is unlikely to represent an outflow from M33. This is because the ionic lines of the VHVC are narrower and more symmetric than those detected in galactic outflows seen down the barrel of nearby galaxies.

There remain three intriguing possibilities highlighted by our analysis. First, the VHVC could be a normal ionized absorber sitting in MW’s CGM. Second, it could be associated with the nearby Wright’s Cloud, which would indicate that Wright’s Cloud does not belong to the Magellanic Stream. Third, it could be part of M33’s northern warp given the similar metallicity and proximity in position–velocity space. If true, the data indicate that M33’s northern warp is folding toward the MW. The VHVC’s metallicity would imply an ISM origin for the warp, favoring the scenario that M33’s warp was formed during a past interaction between M33 and M31. Furthermore, the proximity of the VHVC with Wright’s Cloud and M33’s northern warp may hint that these three objects are physically connected. In this case, Wright’s Cloud would be a Magellanic-like structure in M33’s CGM, which would have important implications on the dynamical history of M33. To break the degeneracy of all these scenarios, further deep H I observations to map diffuse H I gas in this Magellanic-M33-M31 overlapping area would be highly valuable. Absorption-line experiments using MW halo stars toward this direction would also help to bracket (or yield lower/upper limits on) the distance.

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