ORIGIN(S) OF THE HIGHLY IONIZED HIGH-VELOCITY CLOUDS BASED ON THEIR DISTANCES

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ABSTRACT
Previous Hubble Space Telescope and FUSE observations have revealed highly ionized high-velocity clouds (HVCs) or more generally low H\textsc{i} column HVCs along extragalactic sight lines over 70\%–90\% of the sky. The distances of these HVCs have remained largely unknown hindering from distinguishing a “Galactic” origin (e.g., outflow, inflow) from a “Local Group” origin (e.g., warm-hot intergalactic medium). We present the first detection of highly ionized HVCs in the Cosmic Origins Spectrograph spectrum of the early-type star HS 1914+7134 (l = 103°, b = +24°) located in the outer region of the Galaxy at \(d \simeq 14.9\) kpc. Two HVCs are detected in absorption at \(v_{LSR} = -118\) and \(-180\) km s\(^{-1}\) in several species, including C\textsc{iv}, Si\textsc{iv}, Si\textsc{iii}, Al\textsc{ii}, C\textsc{ii}, Si\textsc{ii}, O\textsc{i}, but H\textsc{i} 21 cm emission is only seen at \(-118\) km s\(^{-1}\). Within 17° of HS 1914+7134, we found HVC absorption of low and high ions at similar velocities toward five extragalactic sight lines, suggesting that these HVCs are related. The component at \(-118\) km s\(^{-1}\) is likely associated with the outer arm of the Milky Way. The highly ionized HVC at \(-180\) km s\(^{-1}\) is possibly an HVC plunging at high speed onto the thick disk of the Milky Way. This is the second detection of highly ionized HVCs toward Galactic stars, supporting a “Galactic” origin for at least some of these low H\textsc{i} column density HVCs.

Key words: cosmology: observations – galaxies: halos – galaxies: kinematics and dynamics

Online-only material: color figure

1. INTRODUCTION

The Milky Way is surrounded by large gaseous complexes observed at high velocities (\(|v_{LSR}| \gtrsim 90\) km s\(^{-1}\)), known as high-velocity clouds (HVCs). HVCs were traditionally regarded as neutral entities (e.g., Wakker & van Woerden 1997), but this view has given way to one that recognizes the importance of an ionized component to many of these clouds, thanks to high-quality UV observations from the Hubble Space Telescope (HST) and the Far Ultraviolet Spectroscopic Explorer (FUSE; Sembach et al. 1995, 1999, 2003; Lehner et al. 2001; Lehner 2002; Collins et al. 2004, 2005, 2009; Ganguly et al. 2005; Fox et al. 2004, 2005, 2006; Richter et al. 2009; Shull et al. 2009). Many of these HVCs are almost completely ionized and show absorption from the “high ions” O\textsc{vi}, C\textsc{iv}, and Si\textsc{iv}. These are therefore deemed highly ionized HVCs, although they often show absorption not only in the high ions, but also in the lower ions (e.g., C\textsc{ii}, C\textsc{iii}, and even atoms (H\textsc{i}, O\textsc{i}). A better designation would be multiphase HVCs or low H\textsc{i} column HVCs (see also Fox et al. 2006; Collins et al. 2009).

The covering factor of these low H\textsc{i} column density HVCs is extremely high and much larger than that of the H\textsc{i} 21 cm HVCs. FUSE surveys of active galactic nuclei (AGNs) and quasi-stellar objects (QSOs) show that 60\%–70\% (perhaps even 85\%) of the high-latitude sky is covered by O\textsc{vi} HVCs, the majority of which (\(\sim 75\%\)) have no H\textsc{i} emission counterpart (Sembach et al. 2003; Fox et al. 2006). Shull et al. (2009) and Collins et al. (2009) show that high-velocity Si\textsc{iii} absorption has a detection rate of 80\%–90\% at high latitude. These numbers are to be contrasted to the H\textsc{i} 21 cm emission (\(N(H\textsc{i}) \gtrsim 10^{17.9}\) cm\(^{-2}\)) covering factor of \(\sim 37\%\) (Murphy et al. 1995).

Both galactic and larger-scale phenomena/structures have been invoked for the origin(s) of these HVCs, including galactic feedback processes, disk–halo mass exchange (e.g., through the accretion of matter condensing from an extended corona), or the shock-heated warm-hot intergalactic medium (WHIM) of the Local Group (e.g., Blitz et al. 1999; Sembach et al. 2003; Nicastro et al. 2003; Collins et al. 2005; Fox et al. 2006). Pros and cons of both theories have been discussed, but they are circumstantial and tentative, relying on assumptions of poorly constrained quantities, such as metallicities and ionization conditions. As for the larger H\textsc{i} column density HVCs, the distance of the HVCs is the sole direct test for these competing models.

Previous searches of these types of HVCs in the spectra of Galactic halo stars have mostly failed (Zsarg\'o et al. 2003; Sembach et al. 2003), leading some support to the hypothesis that the highly ionized HVCs could be mainly associated with the WHIM of the Local Group rather than with some galactic-scale phenomena. However, most distance limits for highly ionized HVCs are not very constraining, as the stars in the Zsarg\'o et al. (2003) survey are mostly significantly closer than those against which the higher column density H\textsc{i} HVCs have been detected, 5 kpc \(\lesssim d \lesssim 15\) kpc (e.g., Wakker 2001; Wakker et al. 2008). Further for the stars at large \(d\) in Zsarg\'o et al., the signal-to-noise ratio (S/N) was often not high enough and/or the stellar continua were too complicated to be able to reliably detect O\textsc{vi} at high velocity.

In Zech et al. (2008), we revisited one of the Zsarg\'o et al. stars, the PAGB star ZNG 1 in the globular cluster NGC 5904 (\(z = 5.3\) kpc, see Table 1), with additional FUSE and new HST/STIS (E140M) observations, finding two highly ionized HVCs with no detected H\textsc{i} emission. This firmly demonstrated that some of these HVCs originate near the Galactic disk. For sight lines passing through known large H\textsc{i} complexes (e.g., complex C, Magellanic Stream), highly ionized gas is found with similar kinematics as the neutral HVCs (e.g., Collins et al. 2007; Fox et al. 2004). Kinematics and metallicity arguments also suggest some of low H\textsc{i} column HVCs observed toward the Large Magellanic Cloud (LMC) are due to galactic feedback...
occurring within the LMC (Lehner & Howk 2007; Lehner et al. 2009).

Progress in determining the distances of the highly ionized HVCs seen in the Galactic sky is now possible owing to the recent installation of the Cosmic Origins Spectrograph (COS; and repair of the Space Telescope Imaging Spectrograph, STIS) on board the HST. The high throughput of COS at medium resolution ($R \approx 20,000$) allows us to efficiently observe targets much fainter in the UV than previously, and hence observe more distant stars. In this Letter, we report on the first observations from our COS program to search and characterize the high-velocity $N$ v, C iv, and Si iv interstellar absorption in stars at large distances ($4 \, \text{kpc} < d < 21 \, \text{kpc}$, $3 \, \text{kpc} < |z| < 13 \, \text{kpc}$). Presently, four stars out of 24 have been observed. For two of them (PG1708+142, PG1704+222, PAGB stars at $d = 10$ and 7 kpc, respectively), no HVCs were detected. For another one, the S/N was lower than expected and will need a closer inspection. However, in the COS spectrum of the fourth star (HS 1914+7139, see Table 1), two HVCs at $v_{\text{LSR}} = -180$ and $-118 \, \text{km s}^{-1}$ are detected in C iv, Si iv, C ii, and other species. While the HVC at $-118 \, \text{km s}^{-1}$ is detected in both absorption and H i 21 cm emission and may be associated with the outer arm of the Galaxy, the other HVC is only detected in absorption. Thus, we have found another highly ionized HVC falling toward the Sun and well within the Milky Way.

2. OBSERVATIONS AND ANALYSIS

As HVCs were only detected toward HS 1914+7139, we only summarize here the data for this star. HS 1914+7139 is a (possible runaway) B2.5 IV star ($\log g = 3.9$, $T_{\text{eff}} = 17,600 \, \text{K}$) with a projected rotational velocity $v \sin i = 250 \, \text{km s}^{-1}$ and a radial velocity in the local standard of rest (LSR) frame of $-25 \, \text{km s}^{-1}$ (Heber et al. 1995; Ramspeck et al. 2001). It is located in the outer region of the Galaxy at a distance from the Sun, $d = 14.9 \, \text{kpc}$, and height above the Galactic plane, $z = 6.0 \, \text{kpc}$ (Ramspeck et al. 2001). The distance is accurate to $\sim 20\%$ and is based on detailed model of the stellar atmosphere. The large projected rotational velocity is ideal for interstellar studies removing the possibility that some of the narrow lines observed in the spectrum are stellar.

The COS observations of HS 1914+7139 were obtained on 2009 October 9 using the gratings G130M (1150–1450 Å) and G160M (1405–1775 Å). The exposures times for these two settings were 1.1 and 1.3 ks, respectively, giving S/N $\sim 20$ per resolution element. The UV flux of this star is $(3–5) \times 10^{-14} \, \text{erg cm}^{-2} \, \text{s}^{-1} \, \text{Å}^{-1}$, which would have required several tens of ks with STIS E140M to reach similar S/N. The data were collected in time-tag mode and were processed using the current version of CALCOS (v2.11b) available at the Multi-Mission Archive at STScI (MAST). As the COS mission is still in its infancy, there are many aspects of the data calibration that are not completely optimal. For example, no flat field has been applied to the data and, based on profiles that are known to be fully saturated (see Figure 1), there seem to be issues with the background correction in some locations (possibly owing to some contamination by scattered light). The post-launch line-spread function (LSF) is also more complicated than the pre-launch LSF with the presence of broad non-Gaussian wings, degrading somewhat the resolution of the COS G130M and G185M data (Ghavamian et al. 2009). As we use several absorption lines as well as several transitions of a same ion, these adverse factors do not impede the reliable detection of the HVCs and the measurements of their velocities. However, estimates of the column densities are more subject to the LSF uncertainties, background subtraction, and flat-fielding, and therefore column densities listed in this Letter should be considered as preliminary.

The stellar continuum was simple enough to be fitted with low-order Legendre polynomials ($\leq 4$), and in Figure 1, we show some of the resulting normalized profiles near some of the observed species. In this figure, we also show the 21 cm emission data from the 36’ Leiden–Argentine–Bonn survey (LAB; Kalberla et al. 2005) in the direction of HS 1914+7134. The absorption spectra show two high-velocity components at $v_{\text{LSR}} = -180$ and $-118 \, \text{km s}^{-1}$, but only the latter component is seen in emission. The component at $v_{\text{LSR}} = -180 \pm 5 \, \text{km s}^{-1}$ has absorption of C iv, Al ii, Si ii, Si iii, Si iv, C iv, and O i. All these species (but the weaker line of the C iv doublet) are detected at more than the $3\sigma$ level. The velocity is the average of $v_{\text{r}} = \int_{v_{\text{r}}}^{v_{\text{r}}} v \tau_{\text{a}}(v) dv/\int_{v_{\text{r}}}^{v_{\text{r}}} \tau_{\text{a}}(v) dv$ (where $\tau_{\text{a}}$ is the apparent optical depth) for all the detected absorption lines (except C ii, Si ii $\lambda 1193$, and Si iii that are very strong lines where lower velocity components may contaminate the HVC component). The profiles were integrated from $v_{1} \approx -230$ to $v_{2} \approx -155 \, \text{km s}^{-1}$. For the other component, the same species are observed as well as Si ii, Fe ii, N i, and possibly N v. Integrating the profiles from $v_{1} \approx -155 \, \text{km s}^{-1}$ to $v_{2} \approx -90 \, \text{km s}^{-1}$ of N i, Al ii, Si ii ($\lambda 1304$, 1526), Fe ii, C iv, Si iv, and N v yields $v_{\text{LSR}} = -118 \pm 4 \, \text{km s}^{-1}$ for this HVC, within $1\sigma$ of the H i average emission velocity.

3. RESULTS AND DISCUSSION

HS 1914+7139 is situated at a distance of 14.9 kpc from the Sun and 6 kpc above the Galactic plane. Three main features of the Milky Way cross its path: Orion Spur at $v_{\text{LSR}} \sim -40 \, \text{km s}^{-1}$, the Perseus arm at $v_{\text{LSR}} \sim -75 \, \text{km s}^{-1}$, and the outer arm at $v_{\text{LSR}} \sim -90$, $-120 \, \text{km s}^{-1}$. Based on the weak interstellar lines (e.g., Si ii $\lambda 1250$ and N ii $\lambda 1370$), the average LSR velocity of the low-velocity component is $-37 \pm 3 \, \text{km s}^{-1}$, and hence the low-velocity component mostly probes some relatively nearby gas.

Using the rotation curve from Clemens (1985), a velocity of about $-120 \, \text{km s}^{-1}$ occurs in gas at Galactocentric distance $R_{G} \approx 22 \, \text{kpc}$ in the direction of HS 1914+7139 if the gas corotates with the Galaxy. The Galactocentric distance of the star is $R_{G} = 23.4 \, \text{kpc}$ (assuming $R_{G} = 8.5 \, \text{kpc}$). Hence combining the information from the kinematics and distance

Table 1
Detected Highly Ionized HVCs toward Galactic Stars

| Name       | $l$ (deg) | $b$ (deg) | Sp. Type | $d$ (kpc) | $z$ (kpc) | $v_{\text{LSR}}$ (km s$^{-1}$) | References |
|------------|-----------|-----------|----------|-----------|-----------|-------------------------------|------------|
| NGC 5904/ZNG1 | 3.88      | +46.79    | PAGB     | 7.5       | +5.3      | $(-140, -110)$                | 1          |
| HS 1914+7139 | 102.99    | +23.91    | B2.5 IV  | 14.9      | +6.0      | $(-180, -118)$                | 2          |

References. (1) Zech et al. 2008 and (2) this Letter.
provides support for an origin of the component at $-118 \text{ km s}^{-1}$ from the outer arm, and this is therefore the first firm upper limit on the distance of the outer arm gas. We, however, note that both velocities and distance are also consistent with those of the nearby complex C ($d = 10 \pm 2.5 \text{ kpc}$, Thom et al. 2008, and see also Wakker et al. 2007).

Based on the rotation curve of the Milky Way, the gas moving at $-180 \text{ km s}^{-1}$ corresponds to $R_G \sim 120 \text{ kpc}$ in a corotating disk/halo in the direction of HS 1914+7139. The limit from the distance of the star evidently rejects this hypothesis, implying that this component is a genuine HVC in the sense that its LSR velocity is inconsistent with a simple model of differential Galactic rotation. This is therefore a highly ionized HVC that is much closer than its corotating distance implies. Its high negative velocity suggests it is plunging onto the Milky Way thick disk.

We have already noted above that the sight line to HS 1914+7139 lies near complex C, but the absolute LSR velocity of the present HVC at $-180 \text{ km s}^{-1}$ is substantially larger than those associated with complex C. Searching for other sight lines near HS 1914+7139 with high-velocity gas detected, we found five QSOs/AGNs that are summarized in Table 2. All these lines of sight show both absorption at LSR velocities lower and greater than $-150 \text{ km s}^{-1}$. For the absorption centered near $-120 \text{ km s}^{-1}$, sight lines with typically $b < 28^\circ$ (for $l \sim 90^\circ$–$110^\circ$) are related to the outer arm while HVCs at $b > 30^\circ$ are associated with complex C. However, as Tripp et al. (2003) also discussed, with the current observational evidence it is not clear if complex C and the outer arm gas are different entities or have a relationship, except for the H i maps that indicate that the outer arm seems to connect more smoothly to the Galactic disk than complex C (e.g., Wakker 2001; Tripp et al. 2003).
In what follows (except otherwise stated), we focus solely on the HVCs at $v_{LSR} \lesssim -150$ km s$^{-1}$ where little or no H I 21 cm emission has been detected ($N$(H I) \lesssim 10$^{18.7}$ cm$^{-2}$). Preliminary apparent column densities toward HS 1914+7139 for O i and Si ii are: $\log N$(Si ii) \simeq 13.6, $\log N$(O i) \simeq 13.9, giving [O i]/[Si ii] = -0.9 (where $X/Y = \log N(X)/N(Y) - \log(X/Y)_0$) and the solar abundances are from Lodders et al. (2009), i.e., the gas is dominantly ionized (e.g., Lehner et al. 2001). Using the results from Tripp et al. (2003), [O i]/[Si ii] \simeq -0.53 toward 3C 351, again suggesting a large fraction of ionized gas. Only O vi and C iv are detected toward H 1821+643 (Savage et al. 1995; Oegerle et al. 2000; Sembach et al. 2003; Tripp et al. 2003), implying that the gas is highly ionized. For the other sight lines listed in Table 2, the presence of Si ii or/and other higher ions also implies a large amount of ionized gas. So not only do the HVCs listed in Table 2 and toward HS 1914+7139 share similar velocities, but they all also have low H I column densities and are largely ionized. This suggests they trace a common structure and HS 1914+7139 places these HVCs (or this HVC complex) at $d \approx 14.9$ kpc and $\zeta \approx 6$ kpc.

While the HVC complex at $v_{LSR} \lesssim -150$ km s$^{-1}$ is not part of the WHIM, its exact origin is still uncertain, and includes Galactic gas in a non-circular orbit, or some Galactic fountain material that is raining back on the Milky Way, or some extragalactic material that is being accreted onto the Milky Way. Tripp et al. (2003) denominated the HVC toward 3C 351 the high-velocity ridge (HVR) and favored the latter scenario where the HVR would be the leading edge of complex C that is interacting with the lower halo of the Milky Way based on conjectural arguments from their and others’ observations. Possibly the strongest argument for an extragalactic origin is their derived metallicity of the HVR, ([O i]/H I) \gtrsim -1.2 dex solar, that is consistent with a much lower metallicity than expected from chemical evolution models and abundance measurements in the Milky Way (e.g., Cescutti et al. 2007, where the lowest O abundance has a mean and a deviation of $-0.2 \pm 0.2$ dex at $R_g > 9.5$ kpc). There is some uncertainty in the metallicity of the HVR because H I was not detected in the spectrum obtained from the smaller beam radio telescope but was detected in the spectra obtained from larger beam radio telescopes, possibly because the larger beams detected some H I emission not present in the 3C 351 pencil beam sight line as suggested by Tripp et al. On the other hand, an inspection of the H I spectrum shown in Figure 5 of Tripp et al. suggests that the sensitivity of the smaller beam telescope may be borderline for the low H I column of the HVR. A better understanding of the H I column density in the direction of 3C 351 may eventually shed some light on the origin of this HVC complex.

In summary, these early HST/COS results have successfully constrained the distance of two multiphase HVCs in the direction $l = 103^\circ$ and $b = +24^\circ$. One is related to the outer arm of the Milky Way and the other ones traces infalling gas onto the Milky Way (or possibly some Galactic gas in a non-circular orbit). It is too early to conclude if all the highly ionized HVCs are linked to galactic phenomena rather than the Local Group, but the two detections of highly ionized HVCs in very different regions of the Galaxy (central and outer regions, see Table 1) show that at least some of these low $N$(H I) HVCs are near the Milky Way and likely associated with infalling gas (from a Galactic fountain or accretion of matter condensing from the Galactic corona). We note that so far only negative high velocities have been detected in spectra of stars, and it remains to be seen if highly ionized HVCs with positive velocities are found at $d < 10$–20 kpc from the Milky Way. Once all the observations of our program are completed, we should have a sizeable sample that will help us to better understand the origin(s) of the highly ionized HVCs that cover the Milky Way sky.

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