A Reservoir of Ionized Gas in the Galactic Halo to Sustain Star Formation in the Milky Way

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Without a source of new gas, our Galaxy would exhaust its supply of gas through the formation of stars. Ionized gas clouds observed at high velocity may be a reservoir of such gas, but their distances are key for placing them in the Galactic halo and unraveling their role. We have used the Hubble Space Telescope to blindly search for ionized high-velocity clouds (iHVCs) in the foreground of Galactic stars. We show that iHVCs with $90 \leq |v_{\mathrm{LSR}}| \lesssim 170 \ \mathrm{km\,s^{-1}}$ are within one Galactic radius of the sun and have enough mass to maintain star formation, while iHVCs with $|v_{\mathrm{LSR}}| \gtrsim 170 \ \mathrm{km\,s^{-1}}$ are at larger distances. These may be the next wave of infalling material.

The timescale for gas consumption via star formation in spiral galaxies is far shorter than a Hubble time (13.8 billion years), requiring an on-going replenishment of the gaseous fuel in the disks of galaxies for continued star formation. Analytical models and hydrodynamical simulations have emphasized the importance of cold stream accretion as a means for metal-poor gas (metallicity that is less than 10% solar or $Z \lesssim 0.1 Z_{\odot}$) to flow onto galaxies along dense intergalactic filaments (*1*). However, galaxies may also exchange mass with the local

intergalactic medium (IGM) through outflows driven by galactic "feedback", galactic winds powered by massive stars and their death and from massive black holes. Some of this material may return to the central galaxy as recycled infalling matter – the galactic fountain mechanism ($2, 3$). The circumgalactic medium about a galaxy is thus a complicated blend of outflowing metal-rich and infalling metal-poor gas. The relative importance of these processes is poorly constrained observationally. Here we demonstrate that ionized gas in the local Galactic halo provides a major supply of matter for fueling ongoing star formation.

Inflow and outflow in the Milky Way halo can be studied via the so-called high-velocity clouds (HVCs), clouds moving in the local standard of rest (LSR) frame at $|v_{\mathrm{LSR}}| \geq 90 \ \mathrm{km \, s^{-1}}$ (4). Determining the distance (d) of these HVCs is critical for associating HVCs with flows occurring near the Milky Way rather than the IGM of the Local Group and for quantifying their basic physical properties because several of these directly scale with the distance (e.g., the mass $M \propto d^2$). Major progress has been made in the last decade for some of the large, predominantly neutral HVC complexes, placing them 4–13 kpc from the sun (excluding here the Magellanic Stream) (5–8). About 37% of the Galactic sky is covered by H I HVCs with column densities $N(\mathrm{H \ I}) \geq 10^{17.9} \ \mathrm{cm^{-2}}$ (9), but the infall rate of the largest H I HVC complex within 10 kpc (complex C), $\sim 0.14 \, \mathrm{M_\odot \, yr^{-1}}$ (8), is far too modest for replenishing the 0.6–1.45 $\mathrm{M_\odot \, yr^{-1}}$ consumed by Milky Way star formation (10). This is not entirely surprising given that recent models show that inflowing gas should be predominantly ionized in view of the small amounts of neutral gas available for inflow at any epoch (11). In ionized gas, $N(\mathrm{H \ I})$ becomes small relative to $N(\mathrm{H \ II})$, and the H I emission becomes extremely difficult to impossible to detect. Low H I content HVCs are, however, routinely found in absorption in the spectra of cosmologically distant objects, such as active galactic nuclei (AGNs), with a detection rate of $\sim$60–80% (12–16). Their total (neutral and ionized) hydrogen column density is shown to be quite large (as large as $N(\mathrm{H \ I})$ in predominantly neutral HVCs). These are therefore ionized

HVCs (iHVCs), i.e., $N(\text{H II}) \gg N(\text{H I})$ (*12, 16*). Given their large covering factor, the iHVCs may represent the long sought supply of gas needed for continued Milky Way star formation. However, the iHVCs have been mostly detected against AGNs: they may reside within the Galaxy, the Local Group, or the IGM. Thus, as for their larger H I column density counterparts, direct distance constraints are required for determining their masses and for characterizing their role in the evolution of the Milky Way.

To determine the distances of iHVCs can be directly undertaken by observing the gas in the foreground of stars at known distances from the sun. Recently, based on observations of high-velocity interstellar absorption in the ultraviolet spectra of two Galactic stars, two of these iHVCs were found within 8–15 kpc from the sun (*17, 18*). One of them was found toward the inner Galaxy and has super-solar metallicity, probing gas that has been ejected from and is raining back onto the Milky Way disk (*17*). Another was observed at $l \sim 103°$ with a galactocentric distance of < 17.7 kpc and sub-solar metallicity; it likely traces gas that is being accreted by the Milky Way, possibly associated with the well known large H I complex C (*18, 19*). These studies show that some iHVCs probe gas flows in and out of the Galactic disk, with some originating from the Milky Way and others having an extragalactic origin.

Here we generalize the result to understand these iHVCs in the context of the Milky Way evolution with a survey of the gas in the foreground of 28 distant Galactic halo stars with known distances. These stars were observed with the Cosmic Origins Spectrograph (COS) and Space-Telescope Imaging Spectrograph (STIS) on board the *Hubble Space Telescope (HST)*, and a large majority $(23/28)$ of these were obtained through our *HST* Cycle 17 program 11592 (SOM). The main criterion for assembling this stellar sample is that these UV bright stars are at height $|z| \gtrsim 3$ kpc from the Galactic plane. This minimum height was adopted in view of absence or scarcity of iHVCs at smaller z (*20*) and other works on their predominantly neutral counterparts (*5*). We systematically searched for high-velocity interstellar metal-line absorption

in the COS and STIS UV spectra of these stars (SOM). We noted HVC detections only if high velocity absorption was seen in multiple ions or transitions (at a minimum two, see Fig. 1). We measured the apparent optical depth-weighted mean velocity $\langle v \rangle = \int v\tau_a(v)dv / \int \tau_a(v)dv$ (Table S1). Most of the HVCs seen in absorption against the stars do not have H I 21-cm emission at a level of $\gtrsim 10^{18.5}$ cm^{-2} based on the Leiden/Argentine/Bonn (LAB) survey (21). The column densities of Si II and O I imply large ionization fractions in several HVCs of our sample (Fig. 1, SOM, and (17, 22)), demonstrating that $N(\text{H II}) \gg N(\text{H I})$.

The iHVC detection rate in our stellar sample is 50% (14/28). While a sightline may have more than one high-velocity absorption component, only one HVC for a given sightline is counted for estimating the covering factor. Defining a sample with a more uniform sensitivity $W_\lambda \geq 15$ mÅ near Si II $\lambda 1526$ and with no stellar contamination (i.e., with no observed stellar photospheric absorption at $|v_{\text{LSR}}| \geq 90$ km; see flag $Q = 1$ in Table S1 and SOM for more details) gives essentially the same detection rate with 47% (9/19). The average distance of the stars in the latter sample where the iHVCs are detected is 11.5 ± 4.1 kpc; the average absolute z-height is 7.3 ± 3.0 kpc; for the whole sample these are $\langle d \rangle = 11.6 \pm 6.9$ kpc and $\langle |z| \rangle = 6.5 \pm 3.2$ kpc. Our sky coverage is larger at $b > 0°$ than at $b < 0°$ (Fig. 2); the difference of detection rates between the northern (60%, 12/20) and southern (29%, 2/7) sky may be due to statistical fluctuations in the smaller southern sample. With the better sampled northern Galactic sky, there is some evidence for an increase in the detection rate to 73% (11/15) for sightlines with $z \gtrsim 4$ kpc, implying that most of the iHVCs could be situated at $4 \lesssim z \lesssim 9$ kpc. There is no iHVC absorption at $|v_{\text{LSR}}| \gtrsim 170$ km s^{-1} (VHVCs) toward the stars (Fig. 2, SOM) even though these are observed along the path to AGNs (Fig. 2, SOM, and see below). Thus there is no evidence for VHVCs in the Galactic halo at $|z| \lesssim 10$ kpc.

In order to understand the implications of the iHVC detection rate toward stars, we need to compare it to a distance-independent measure of the iHVC covering fraction. Earlier studies

determined the covering factors of these iHVCs toward AGNs (*12–14,16*), but they concentrated on a single species (O VI or Si III), which differs from our search method. We combined observations from (*15*) and (*14*) to assemble an AGN sample using the same search criteria adopted for our stellar survey (i.e., using the same metal ions) (SOM). Our AGN sample is summarized in Table S2 and its sky distribution is shown on Fig. 2. It has a similar sensitivity and size as the stellar sample. The detection rate is 67% (16/24) for the iHVCs and 42% (11/26) for the VHVCs (excluding the 4 Magellanic Stream sightlines). For the HVC sample, 6 sightlines with H I LAB emission at $90 \leq |v_{\mathrm{LSR}}| \leq 170 \ \mathrm{km\,s^{-1}}$ were excluded because of strong selection effects in the AGN sample: many of these AGNs were indeed initially targeted to study known H I HVCs (including these sightlines yields $f_c = 73\%$). After removing those, the AGN sample may still be biased and overestimate the true covering factors because a given AGN could have been specifically targeted for studying an HVC or could have been favored over other AGNs because of previously known HVCs near the line of sight.

The covering factors of the iHVCs are therefore $f_c = 50\%$ (14/28) and $\leq 67\%$ (16/24) for the stellar and AGN samples, respectively. Hence a majority (if not all) of the iHVCs seen toward AGNs are within $\langle d \rangle \simeq 12 \pm 4$ kpc and $\langle |z| \rangle \simeq 6 \pm 3$ kpc, implying that the iHVCs at $90 \lesssim |v_{\mathrm{LSR}}| \leq 170 \ \mathrm{km\,s^{-1}}$ mostly trace flows of ionized gas in the Milky Way halo. On the other hand, VHVCs must then lie beyond $d \gtrsim 10$–20 kpc ($|z| \gtrsim 6$–10 kpc) because they are not detected toward any star. The VHVCs could be associated with the outer reaches of the Milky Way or gas in the Local Group. In the former scenario, this would imply that iHVCs slow through their interaction with the Galactic gas as they approach the plane, as predicted by some models of HVCs (*23–26*). In the latter scenario, some of the VHVCs could be at large distances from the Milky Way or other galaxies (e.g., Andromeda) and be a component of the multiphase local intergalactic medium, which may permeate the Local Group of galaxies (*27,28*).

We note that a majority of the so-called O VI HVCs have accompanying C III and H I HVC

absorption at similar high velocities, demonstrating their multiphase nature (*13*). The velocity sky-distribution of the O VI, Si III, and H I HVCs are also alike (*12–14*), and the sky-distribution of the iHVCs seen toward the AGNs and stars is moreover remarkably similar considering our better sampled north Galactic sky (Fig. 2). These and the fact that the H I HVCs and iHVCs are now known to be at similar distances strongly suggest they are all related, probing separate phases where the H I HVCs may be the densest regions of the more diffuse ionized complexes.

Having demonstrated the iHVCs are in the local Galactic halo, we can reliably estimate their mass and assess their importance for future star formation in the Milky Way. The mass of these iHVCs can be estimated $M_{\mathrm{iHVC}} \simeq 1.3 m_{\mathrm{H}} (4\pi d^2) f_c N_{\mathrm{H\,II}} \approx 9.6 \times 10^{-12} (d/12\,\mathrm{kpc})^2 (f_c/0.5) N_{\mathrm{HII}}$ $\mathrm{M_\odot}$ (where m_{H} is the mass of hydrogen and the factor 1.3 accounts for the additional mass of helium). The ionized gas probed by Si II, Si III, and Si IV has $\langle N_{\mathrm{H\,II}} \rangle \approx 6 \times 10^{18} (Z/0.2 Z_\odot)^{-1}$ $\mathrm{cm^{-2}}$ (*16*) while the O VI phase has $\langle N_{\mathrm{H\,II}} \rangle \approx 4.5 \times 10^{18} (Z/0.2 Z_\odot)^{-1}$ $\mathrm{cm^{-2}}$ (*12, 13, 16*), where the metallicity of $0.2 Z_\odot$ is representative of complex C and other large H I complexes (*5, 19*). As O VI and Si III are not expected to exist in the same gas phase, the total H II column density is a sum of the phases traced by these ions, $N_{\mathrm{H\,II}} \approx 1.1 \times 10^{19} (Z/0.2 Z_\odot)^{-1}$ $\mathrm{cm^{-2}}$. These assumptions imply a total mass $M_{\mathrm{iHVC}} \approx 1.1 \times 10^8 (d/12\,\mathrm{kpc})^2 (f_c/0.5) (Z/0.2 Z_\odot)^{-1}$ $\mathrm{M_\odot}$. We estimate infall times of 80–130 Myr assuming infall velocity of about 90–150 $\mathrm{km\,s^{-1}}$, which implies a mass infall rate for the ionized gas of $\sim$ 0.8–1.4 $\mathrm{M_\odot\,yr^{-1}}$ ($d = 12$ kpc, $f_c = 0.5$, and $Z = 0.2 Z_\odot$). While this value may be reduced somewhat because there must be a mixture of outflows and inflows, large H I complexes have subsolar abundances (*5*), suggesting a substantial fraction of the circumgalactic neutral and ionized gas is infalling. Some of the outflowing gas must also be recycled via a Galactic fountain as the iHVCs do not reach the Milky Way escape velocity. We did not bracket the distances of the iHVCs, but their distances are unlikely to be much smaller than 3 kpc as otherwise they would already have been detected serendipitously in the UV spectra of more nearby stars (*20*). If all the iHVCs were at $d = 5$

kpc, the infall rate would still be significant with ~ 0.4–0.6 M$_\odot$ yr^{-1}.

Although the infall rate depends on several parameters that are not well constrained, our distance estimates allow us to unambiguously place the iHVCs at $90 \leq |v_{\mathrm{LSR}}| \leq 170$ km s^{-1} in the Milky Way's halo. Assuming an average metallicity of $0.2Z_\odot$, the estimated infall rate is a factor 6–10 larger than that of the large H I complex C (*6*, *8*). (Even with an unrealistically solar metallicity value for all the iHVCs, their infall rate would still be important.) The present-day total star formation rate of the Milky Way is 0.6–1.45 M$_\odot$ yr^{-1} (*10*), and chemical evolution models require a present-day infall rate of only 0.45 M$_\odot$ yr^{-1} (*29*), a value that could be somewhat reduced according to stellar mass loss models (*30*). The iHVCs are thus sufficient to sustain star formation in the Milky Way.

We have implicitly assumed the HVCs survive their fall onto the Galactic disk. Hydrodynamical simulations of HVCs support this idea (*25,26*). In these models, the HVCs lose most of their H I content within 10 kpc of the disk and continue to fall toward the disk as warm ionized matter. This is consistent with the iHVCs covering more Galactic sky and tracing a larger mass reservoir than the predominantly neutral HVCs. As the iHVCs are still overdense relative to the halo medium, they can continue to sink toward the Galactic plane where they decelerate and feed the warm ionized medium (Reynolds layer) 1–2 kpc from the Galactic disk. In the Reynolds layer, the clouds have low velocities and cannot be identified as HVCs anymore, but as low- or intermediate-velocity clouds, consistent with the observed absence of iHVCs at low z-height. In this scenario, VHVCs are also not expected to be seen near the Galactic disk as the HVC velocities decrease with decreasing z-height due to drag. This is consistent with the lack of VHVCs at $|z| \lesssim 10$–20 kpc and the observed velocity sky-distribution (*23*).

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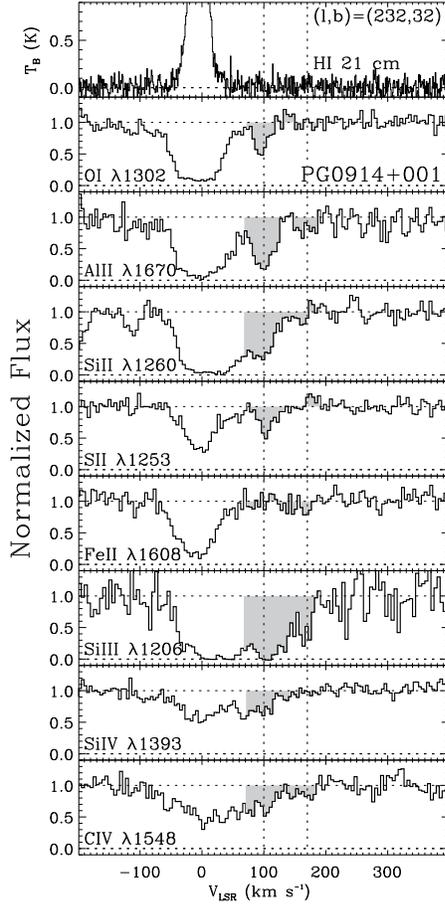
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Figure 1: Example of COS continuum normalized absorption profiles of various metal-lines and LAB H I emission line profile (*top panel*) toward PG0914+001, a star at $d = 16$ kpc and $z = +8.4$ kpc. There are at least two iHVCs seen in absorption at $+100$ and $+170$ km s^{-1} indicated by the dotted lines and shaded regions. The ~ 0 km s^{-1} absorption and H I emission are from the Milky Way disk. We derive $[\mathrm{O\,I/S\,II}] \equiv \log(N(\mathrm{O\,I})/N(\mathrm{S\,II})) - \log(A_\mathrm{O}/A_\mathrm{S})_\odot \simeq -2.34$, implying $\mathrm{H\,II} \gg \mathrm{H\,I}$. If the iHVC has a solar abundance, $N(\mathrm{H\,II}) > 10^{19.6}$ cm^{-2} (based on S II) and $N(\mathrm{H\,I}) \simeq 10^{17.30}$ cm^{-2} (based on O I). These column densities would increase if the iHVC metallicity is subsolar. We find very subsolar $[\mathrm{Fe\,II/S\,II}] < -1.5$ and $[\mathrm{Si\,II/S\,II}] \simeq -1.4$ ratios, indicating strong ionization and dust depletion effects; the latter could suggest a Galactic origin. Examples of negative-velocity iHVCs toward stars can be found in (*17, 18*).
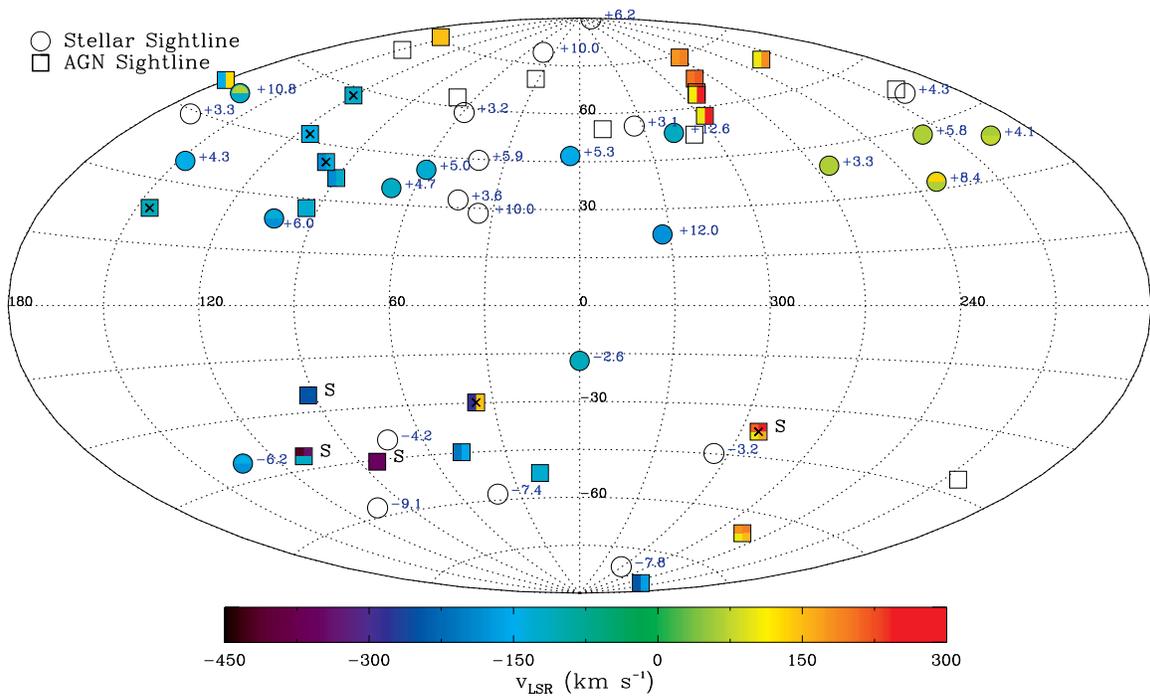
Figure 2: Aitoff projection Galactic (longitude, latitude) map of the survey directions for the stellar sample (circles) and extragalactic sample (square). A colored circle/square indicates an HVC in the foreground of the star/AGN while blank circle/square implies no HVC along the stellar/AGN sightline. The velocity value is color coded following the horizontal color bar. The positive and negative numbers indicate the z-height (in kpc) of the stars. The squares with a X are HVCs where H I 21-cm LAB emission is present at similar velocities seen in absorption. A S near a square indicates a sightline that passes through the Magellanic Stream.