Distance Estimation of the High-velocity Cloud Anti-center Shell (Postprint)

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Abstract

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Full Text

Preamble

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Distance Estimation of the High-velocity Cloud Anti-center Shell

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Abstract

High-velocity clouds (HVCs) are interstellar gas clouds whose velocities are incompatible with Galactic rotation. Since the first discovery of HVCs in 1963, their origins have been debated for decades but remain unsettled, primarily due to the lack of vital parameters such as distance. In this work, we determined the distance to the HVC known as the Anti-center Shell (ACS). We traced the ACS using extinction derived from K-giant stars with known distances and using the diffuse interstellar band (DIB) feature at 5780 Å fitted on spectra of O- and B-type stars with distance estimates. As a result, we provide a lower limit distance for the ACS of 8 kpc, which extends the previous lower limit outward by approximately 4 kpc. A byproduct of the DIB method is the detection of a bar-shaped structure with unusually high positive line-of-sight velocity. Its shape extends along the (l, b) = (155, −5)° sight line and shows a slightly increasing trend in equivalent width and velocity as distance increases.

Key words: galaxies: ISM -Galaxy: kinematics and dynamics -ISM: clouds -(ISM:) dust, extinction -ISM: lines and bands

Introduction

High-velocity clouds (HVCs) are neutral or ionized gas clouds in the vicinity of the Milky Way (MW) characterized by velocities incompatible with Galactic differential rotation (Wakker & van Woerden 1997). Traditionally, astronomers selected HVCs by applying a crude and invariable cut in line-of-sight velocity in the local standard of rest (LSR) reference frame, such as |vLSR| 90 km s^{-1}. Subsequently, an improved definition was proposed by Wakker (1991), who introduced a so-called deviation velocity vdev = 50 km s^{-1} to characterize HVCs as deviating by a fixed velocity separation from the maximally permissible velocity of the Galactic disk in a given direction. Recently, Westmeier (2018) assumed a simple cylindrical model of the Galactic disk with a disk radius of 20 kpc, a disk height of 5 kpc, and a deviation speed of vdev = 70 km s^{-1} to produce velocity masks for filtering out disk components based on the all-sky H I 4π survey (HI4PI; HI4PI Collaboration et al. 2016), a database for Galactic H I emission. The map of Westmeier (2018) offers a comprehensive and high-resolution view of HVCs and has become the cornerstone of this field.

Apart from H I 21 cm observations, another observational technique for HVCs that deserves equal attention is the absorption-line method, by which HVCs can be detected in absorption toward bright background halo stars or quasars, mostly at ultraviolet wavelengths (Smoker et al. 2011; Marasco et al. 2022). While 21 cm H I observations provide a uniform all-sky HVC map (Westmeier 2018), the absorption-line method can probe much lower hydrogen column densities and detect ionized material in HVCs (e.g., Sembach et al. 2000; Lehner et al. 2001; Sembach et al. 2003).

Despite nearly six decades having passed since the initial detection of HVCs in 1963 (Muller et al. 1963), their enigmatic origin persists as an unresolved problem. Based on current observations, HVCs require at least three formation mechanisms: one for the Magellanic Stream and its associated clouds, one for the Outer Arm Extension, and one for the remaining HVCs. Existing hypotheses can be roughly categorized into four groups according to the locations of HVCs: (1) HVCs are situated in the solar neighborhood, indicating they originated from nearby supernova explosions (e.g., Heiles 1979); (2) HVCs are gas at the disk-halo interface, indicating transfer between these regions (e.g., Marasco et al. 2022); (3) HVCs are situated in the Outer Galaxy, e.g., as a polar ring wrapping our MW or as gas stripped or ejected from dwarf galaxies (e.g., Davies 1972); (4) HVCs stem from an even more distant location, as gas from the Local Group or as infalling intergalactic matter (e.g., Verschuur 1969).

Intriguing as the origin theories are, it is vital to pin down the fundamental properties (e.g., distance, metallicity, and 3D kinematics) of HVCs to understand the detailed origin mechanisms. Distance measurement is critical since it helps distinguish which categories the birth of HVCs might fall into, as well as quantify their fundamental physical properties, several of which directly scale with distance (e.g., total mass, size, density, pressure; Wakker & van Woerden 1997). However, distance determination for HVCs is challenging. The most commonly used method is the absorption-line method (Schwarz et al. 1995). Absorption line features produced by HVCs can be explored with spectroscopic observations of background objects with known distances, providing constraints on metallicity, velocity, and distance (upper and lower limits). Considerable work using the absorption-line method has been published (e.g., Schwarz et al. 1995; Ryans et al. 1997; Wakker 2001; Smoker et al. 2006; Thom et al. 2006; Wakker et al. 2007, 2008; Thom et al. 2008; Lehner & Howk 2010; Smoker et al. 2011; Tripp & Song 2012; Peek et al. 2016; Lehner et al. 2022). However, the absorption-line method has difficulty providing precise distances to HVCs because it suffers from the limitation of sparsely distributed tracer stars (Marasco et al. 2022) due to the scarcity of ultraviolet band spectra.

In this paper, we use interstellar extinction to trace the HVC Anti-center Shell (ACS) and constrain its distance. When starlight penetrates gas and dust, its energy is attenuated by absorption or scattering, a process called interstellar extinction. Generally, atomic cloud regions have higher densities, so extinction along the HVC sight line increases more than in the surroundings. The location of the extinction excess reveals our distance to the cloud. Yan et al. (2019,

2021) and Zucker et al. (2019), Wang et al. (2020) have all successfully measured distances to various types of objects, such as molecular clouds and supernova remnants (SNRs), using the extinction method. Numerous and extensively distributed K giants in the MW, which serve as our extinction tracers, can help derive much more precise distances. Hence, they can be used to probe the inner three-dimensional structure of the ACS with the extinction method. Meanwhile, to take advantage of the velocity information from H I 21 cm emission observations, we use the Diffuse Interstellar Band (DIB) feature as an auxiliary tracer to independently verify the position of the step-like pattern in the distance-extinction plot caused by the ACS.

The paper is structured as follows. In Section 2, we describe the sample we used and our filtering strategy. Section 3 describes how we utilized extinction and DIBs to locate the HVC ACS. Section 4 presents the main results from these methods, in which we provide the lower distance limit of the ACS and report a newly discovered positive-velocity high-velocity DIB clump. We further discuss these results in Section 5. The final section summarizes our main findings and discusses possible future improvements.

Cloud Properties

The ACS is a shell-like low-latitude HVC located in the direction opposite to the Galactic center from our solar system (Westmeier 2018). This shell has a 40° diameter and a mean line-of-sight velocity in the LSR of -100 km s^{-1}. The ACS was chosen as our target because: (1) It is located in the anti-center region with low Galactic latitude, making it plausible to be found within 6 kpc from the Sun, where Gaia distance data remain valid; (2) Previous work suggested that the ACS might require an independent origin theory (Wakker & van Woerden 1997). Distance measurement can constrain its formation mechanism and provide insights into its interactions with the surrounding environment.

Spectroscopically Identified Parameters of K Giants from LAMOST Data Release 5

We employed interstellar extinction to illustrate the spatial distribution of the ACS since both dust and gas particles in the cloud generate extinction (Draine 2003). K-giant stars are commonly used tracers in extinction/reddening studies because of their brightness and abundance, making them substantially observed throughout the MW (Xue et al. 2016).

The Guo Shou Jing Telescope (LAMOST) is a 4 m special quasi-meridian reflecting Schmidt telescope located at Xinglong Observatory of the National Astronomical Observatories, Chinese Academy of Sciences (Cui et al. 2012). It recently completed its twelfth data release, enabling global access to an unprecedentedly large amount of low- and medium-resolution stellar spectra of over 17 million stars. Xu et al. (2020) compiled a catalog of K-type giant stars using LAMOST DR5, which aligns well with the objectives of this study. Atmospheric parameters (e.g., effective temperature Teff and surface gravity log g) determined using the Stellar LAbel Machine (SLAM; Zhang et al. 2020) can be extracted from this catalog. According to Xu et al. (2020), K-giant stars in LAMOST were selected following the criteria presented in Liu et al. (2014):

Teff $<$ 5600 K,
log g $<$ 3.5

Here, Teff and log g stand for effective temperature and surface gravity, respectively. They also conducted a metallicity cut of [M/H] > -1.2 to avoid halo stars, which nicely favors our work since this alleviates the influence of metallicity on color.

We additionally adopt a quality cut on the g-band signal-to-noise ratio snrg to ensure the reliability of the effective temperature Teff:

snrg $>$ 20

Bailer-Jones et al. (2021) recommended using the various quality fields in the main Gaia catalog of EDR3 for quality filtering purposes, rather than using flags to select high-quality distance estimates. We used the following constraints in this study:

RUWE $<$ 1.4,
ipd_{{{gof}}*{{harmonic}}}*{amplitude} $<$ 0.1

To ensure reliable statistical analysis, the number of sources needs to be large enough in each 100 K wide effective temperature bin. Therefore, we only kept stars in the temperature range:

4200 K $<$ Teff $<$ 5300 K.

2MASS All Sky Data Release: Point Source Catalog

The Two Micron All Sky Survey (2MASS) is an all-sky survey using two 1.3 m telescopes located at Mount Hopkins, Arizona, and Cerro Tololo, Chile. This survey encompasses three near-infrared passbands, namely J, H, and KS. The photometry was verified to have approximately 0.02 mag accuracy (Skrutskie et al. 2006).

We adopted the J- and KS-band photometry from the 2MASS data to derive the color index J $-$ KS. We made a cut on the photometric quality flag ph_{qual} to keep only sources with flag value A, which is set based on signal-to-noise ratio, measurement quality, and detection statistics. Additionally, a cc_{flg} screening was included to remove sources likely contaminated by proximity. The precise description of these flags can be retrieved from the 2MASS documentation. Here, the asterisks indicate that we did not place any constraint on the photometry quality of the H-band data.

Bailer-Jones' Distance Estimation Based on Gaia EDR3

We adopted the distance estimates from Bailer-Jones et al. (2021), which are based on the Gaia EDR3 Catalog. This work estimated distances for 1.47 billion objects in Gaia EDR3 using a Bayesian approach based on a prior built from a three-dimensional Galactic model that considered interstellar extinction and the magnitude limit of Gaia. Two types of distances are provided: geometric distance, which only uses Gaia EDR3 parallax and the geometric prior, and photogeometric distance, which adds color and apparent magnitude for extra constraints. We chose to use the geometric distance rgeo in this work to avoid introducing color and magnitude dependencies.

Diffuse Interstellar Band (DIB) Feature as the Cloud Tracer

Catalog of 16,002 O- and B-type Stars from LAMOST

The DIBs are a large set of absorption features that arise in interstellar gas (Herbig 1995). In this work, we focused only on the absorption at about 5780 Å, which has been validated as highly correlated with the intensity of interstellar reddening and H I 21 cm emission (Herbig 1995; Lan et al. 2015). It is convenient to extract the DIB $ $5780 from the spectra of O- and B-type stars since they show few other stellar features at this wavelength.

The catalog of 16,002 O- and B-type stars from LAMOST by Xiang et al. (2021) is perfectly suited for this process, so we selected O- and B-type stars in the ACS direction from their catalog and downloaded corresponding low-resolution spectra from LAMOST Data Release 8.

Extinction as the Cloud Tracer

Because the attenuation of light by interstellar extinction is wavelength-dependent, being more efficient at bluer wavelengths, stellar light is typically reddened when it penetrates through the interstellar medium (Draine 2003). The interstellar extinction (Aλ) and reddening (characterized by the color excess E(J − KS)) are therefore highly correlated, and their relationship is described by the extinction law (Wang & Chen 2019). Given the definition of excess interstellar reddening, we calculated the color excess E(J − KS) of the K-giant stars using the equation:

E(J − KS) = (J − KS)obs − (J − KS)0

where (J − KS)obs denotes the observational color and (J − KS)0 is the intrinsic color of the stars.

We determined the intrinsic color (J − KS)0 by assuming the bluest star at a specific effective temperature represents the intrinsic color at that temperature. According to Ducati et al. (2001), Wang & Jiang (2014), and Xue et al. (2016), for tracer stars distributed sufficiently broadly in space, the bluest stars can be treated as a reference without extinction.

In practice, we divided the K-giant stars into 100 K wide effective temperature bins and computed the median color of the top 5% bluest stars in each bin. We then fitted this relation with a cubic polynomial to obtain an effective temperature-intrinsic color relation. The resulting blue edge is plotted in Figure 1 [Figure 1: see original paper]. With this relation, we can determine the reddening for every star using Equation (6).

To extract the extinction excess caused by the ACS alone, we first identified tracer stars projected inside the cloud profile and those surrounding the cloud as a control group. By comparing the two, the cloud signal can be highlighted. We exploited the all-sky HVC map constructed by Westmeier (2018) to create an ACS mask. Stars located within the 21 cm H I emission region of the ACS are assigned to the "on-cloud" group, while others are assigned to the "off-cloud" control group. The cloud profile is illustrated in Figure 2 [Figure 2: see original paper], color-coded by its logarithmic H I column density and radial velocity in LSR.

With stars distributed "on" the cloud, we can trace extinction variation along the ACS sight line. The next step involves classifying these stars into distinct distance intervals. We chose 200 pc as the bin size, which strikes a balance between maintaining acceptable measurement errors and ensuring sufficient resolution of fine structure within the variation curve.

By shifting our temperature-intrinsic color relation line (the "bluest edge") to minimize the difference between the stars in each distance bin and the shifted bluest edge in the distance-color plot, we obtain the mean reddening suffered by these tracers as the amount of displacement applied to the bluest edge. The resulting extinction variation curve is shown in Figure 3 [Figure 3: see original paper], with error bars reflecting comprehensive uncertainty including the uncertainty of the blue edge, observational distance measurement uncertainty, J-band and KS-band photometry uncertainties, and Poisson error from binning the data into sight lines and distance bins. The detailed error estimation process is described in the Appendix.

The ACS is an HVC in the low-latitude region, which is uncommon among the HVC family (Westmeier 2018). This complicates identification of the exact step-like pattern produced by the ACS because the presence of the Galactic disk and its extensive dust leads to substantial additional foreground/background extinction. As depicted in Figure 3, several "stairs" appear as distance increases, resulting from different sub-structures. Consequently, including a control group is necessary. The control group encompasses a larger area beyond the cloud and is confined within Galactic longitude $135° < l < 220°$ and Galactic latitude $-5° < b < 25°$. To avoid excessive information loss from averaging over such a large region, we grouped samples by latitude, splitting both on-cloud and off-cloud groups into low-latitude, medium-latitude, and high-latitude components and comparing derived extinction variations within the same latitudes, as illustrated in Figure 4 [Figure 4: see original paper]. The major differences in overall E(J – KS) growth among these curves originate from global extinction variation in the MW, with detailed analysis presented in Section 4.

Diffuse Interstellar Band (DIB) Feature as the Cloud Tracer

From the spectra of O- and B-type stars, we can extract the line center and equivalent width of the interstellar absorption feature at $ $5780 through straightforward Gaussian fitting, with the continuum estimated and subtracted using the iterative method described in Zhao et al. (2021).

The iterative continuum fitting process from Zhao et al. (2021) began by fitting the $ 5780*localspectrumwithasecond−orderpolynomialandcalculatingthestandarddeviationoffluxdifferen* The process was iteratively repeated 20 times using the remaining valid pixels and replacement points, with the final polynomial fit serving as the continuum for renormalization.

The line center can be converted into the line-of-sight velocity (radial velocity) of the DIB $ $5780 carrier, while the absorption intensity, quantified by equivalent width, has been established by previous studies to exhibit strong correlation with both reddening level and 21 cm H I emission (Herbig 1995; Lan et al. 2015). Consequently, this method allows us to construct not only a distance-reddening plot (in this case taking the form of a distance-equivalent width plot) but also introduces an additional crucial dimension: radial velocity. The inclusion of velocity measurements enables us to identify signals associated with HVCs in H I observations.

After fitting the continuum and line center, we performed quality cuts to retain reliable DIB $ $5780 detections. First, we required spectrum signal-to-noise ratio snrg > 35 to ensure adequate quality for DIB $ $5780 measurement. We also required equivalent width to error ratio EW5780/EW5780_{err} > 4 to count as "detection" of the DIB $ $5780 feature (otherwise considered "non-detection"). Finally, we checked our data on the equivalent width-reddening plot (EW − E(B − V)), excluding points that deviated explicitly from a linear relation. Specifically, we fitted the EW − E(B − V) distribution to a linear relation and calculated the standard deviation σ of our data from this relation, excluding data points deviating more than 3σ.

To filter out DIB $ $5780 detections with velocities incompatible with Galactic differential rotation (referred to as high-velocity DIBs, or HV-DIBs), we applied the method employed by Westmeier (2018) to screen HVCs in H I 21 cm emission data. We adopted the rotation curve by Clemens (1985) and projected this rotation velocity onto the line-of-sight direction using Equation (3) in Westmeier (2018):

vproj = vrot × (R0/R) × sin(l) × cos(b)

where rxy equals the projection length of the Galactocentric distance onto the xy-defined Galactic plane.

Assuming the Galactic disk is a cylinder with R0 = 8.5 kpc and zmax = 5 kpc (the same values as set by Westmeier 2018), we can calculate the distance range [dproj,min, dproj,max] encountered between the Sun and the boundary of the cylindrical disk model at a given (l, b). We considered DIB $ 5780withradialvelocitydeviatingmorethan70kms^{-1}$ from this range as HV-DIB, with uncertainty in velocity determination accounted for by Equation (9). The result is shown in Figure 5 [Figure 5: see original paper]. Gray dots represent all reliable DIB measurements selected with the above criteria, while the shaded area represents the velocity range permitted by Galactic differential rotation, with normal velocity dispersion on the disk included in the deviation velocity vdev = 70 km s^{-1}. HV-DIB measurements (DIBs with anomalous velocity) are marked with asterisks and color-coded by equivalent width.

Both negative-velocity and positive-velocity HV-DIBs appear in Figure 5. Since the ACS is a negative-velocity HVC moving toward us, we should primarily examine these negative-velocity HV-DIB points to see if they are statistically clustered to form a sub-structure like the ACS, which will be discussed in Section 4.

Results

This section discusses the main results from the extinction method and the DIB method described in Section 3.

Bimodal Distribution in Distance-Reddening Scatter Plot

In Figure 3, the curve drawn with tracer stars projected on-cloud shows several step-like patterns. However, none appears solely in the on-cloud plot according to Figure 4. The first two significant extinction steps at 1 kpc and 2 kpc are probably caused by the Local Arm and the Perseus Arm (Xu et al. 2023).

Since averaging reddening E(J − KS) in Figure 4 may wipe out essential information, we recalculated individual reddening for all K-giant stars and produced a scatter plot in Figure 6 [Figure 6: see original paper]. Two separated components appear in both plots: a high-extinction component probably stemming from sight lines passing through the dusty Galactic disk, and a low-extinction component passing through the higher-latitude low-density regime.

We manually separated these components in Figure 6 and illustrated their distribution in Galactic longitude-latitude (glon-glat) space in Figure 7 [Figure 7: see original paper]. The high-extinction components, both in on-cloud and off-cloud groups, are predominantly concentrated in low-latitude regions, likely associated with the structure of the Galactic disk. In contrast, low-extinction components are located at higher latitudes. This spatial distribution provides further support for our explanation of the bimodal pattern in Figure 6. We used a solid red line to specify the approximate boundary between low-extinction and high-extinction components in Figure 7. The edge between high and low extinction regimes appears tilted, potentially indicating a warp in the interstellar dust distribution within our Galaxy (Freudenreich et al. 1994).

We regrouped these components according to their spatial distribution relative to the solid red line in Figure 7 and calculated mean reddening E(J − KS) in distance bins to extract the primary variation trend. Using the same color scheme as Figure 7, we plotted the distance-mean reddening curve for the spatially reclassified components in Figure 8 [Figure 8: see original paper]. In principle, the two low-extinction groups offer a better chance to reveal the ACS as a step in the reddening-distance plot because contamination from the disk can be avoided. However, we find no significant difference beyond 2 kpc. The difference at around 1–2 kpc between these two low-extinction curves is probably due to residual impact from the Local Arm and Perseus Arm rather than the ACS.

Negative Velocity HV-DIBs and Distance Lower Limit of Anti-center Shell (ACS)

With extinction and distance, we can only identify the step produced by ACS through comparisons of extinction variation in different regions. This method becomes less effective when the signal is weak. However, the DIB method provides velocity information at each point, allowing us to screen out anomalous velocities incompatible with the Galactic disk. Since the ACS is a negative-velocity HVC, we first inspected the negative-velocity HV-DIBs in Figure 5 to see if they display any statistical structure in space. In Figure 9 [Figure 9: see original paper], HV-DIBs with negative velocity show no clustering behavior at the same position as the ACS' s 21 cm H I emission in three-dimensional space, indicating no significant signal from the ACS in the DIB measurements.

This non-detection allows us to establish a lower limit for the ACS distance. We excluded stars with unreliable Bailer-Jones distances whose signal-to-noise ratio (SNR) values are smaller than one (where SNR is defined as D/(D_{HIGH}-D_{LOW})). Eventually, we identified a star with Bailer-Jones distance 8.1 ± 1.8 kpc that provides the final distance lower limit.

Discussion

Stacked Spectra for the Diffuse Interstellar Band $ $5780 in the Cloud Region

We stacked spectra of O- and B-type stars projected onto three selected regions (shown in Figure 10 [Figure 10: see original paper]) to enhance potential ACS signals. Prior to stacking, each spectrum was normalized by dividing by its continuum. The on-cloud experimental group, marked with green crosses in Figure 10, excludes stars below the tilted line in Figure 7 to minimize disk contamination. Two off-cloud control groups, marked with blue and orange crosses, were selected at sufficient distances from the ACS cloud to avoid potential interference from its outer ionized regions. The continuum was calculated following the methodology described in Section 3.2 (Zhao et al. 2021).

Figure 11 [Figure 11: see original paper] presents the results: the green solid line shows the stacked spectra of stars in the cloud region, while blue and orange dashed lines represent stacked spectra from off-cloud control regions. The DIB \$ \$5780 peaks align across all three regions, with no bimodal structure observed in the negative-velocity (left-wing) portion of the absorption feature for experimental group stars. While the DIB \$ $5797 featureintheon-cloudsamplespectrumappearsshiftedtowardmorenegativevelocities, Gaussianprofilefittingyieldsavelocityo$ $32.6kms^{\text{\{-1\}}, significantlydifferentfromtheACSvelocityofvLSR\sim-100kms}$\{-1\}\$. These results further support our non-detection of the ACS using the DIB method.

Explanations for Non-detection of the Anti-center Shell

Non-detection of the negative-velocity HVC ACS in both the extinction and DIB methods can be interpreted as a distance limitation of our tracers, allowing us to deduce a lower limit for the HVC. Non-detection may also be caused by the sensitivity limits of our methods, as the ACS signal may be concealed by the strong component of the Galactic disk. Another explanation might be that the neutral hydrogen and dust in the ACS are insufficient to cause remarkable extinction excess. Figure 2 shows the densest part of the cloud has an H I column density of 2×10^{20} cm^{-2}. According to the E(B − V) − NHI relation in Figure 11 of Lan et al. (2015), this column density corresponds to negligible E(B − V). The cloud may also be too hot to harbor dust and DIB carriers that would produce significant extinction, causing our methods to fail. This explanation assumes the ACS composition is similar to the all-sky cloud average in the MW, allowing application of the NHI − E(B − V) relation from Lan et al. (2015), though this is not necessarily true.

Positive Velocity HV-DIBs

Although negative-velocity HV-DIBs show no statistical clustering, positive-velocity ones present intriguing clues. In Figure 12 [Figure 12: see original paper], DIBs at (l, b) = (155, −5)° show clustering characteristics in all three plots: clumpy-shaped in the glon-glat plot and bar-shaped in plots relevant to distance. We revisited our spectrum fitting results for these positive-velocity HV-DIBs and retained well-fitted ones to plot in the X-Y plane in Figure 13 [Figure 13: see original paper] to examine integrated variation in velocity and equivalent width along the strip-like structure. We plotted eye-check results of spectrum fitting for stars with positive-velocity HV-DIB detection in Figure 14 [Figure 14: see original paper], with reliable measurements on the left and unreliable ones on the right.

Both line-of-sight velocity in the Galactic Standard of Rest (GSR) reference frame and equivalent width show a roughly increasing sequence along the pattern, indicating the high-velocity DIB structure has some extent of thickness along the (l, b) = (155, −5)° sight line. The velocity gradient in the structure is not very pronounced, ranging from about 200 to 250 km s^{-1} in GSR when moving outward. Equivalent widths detected in stellar spectra down the stripe rise from about 0.3 to 1.1 Å, meaning background starlight at greater distance passes through thicker DIB clouds or diffuse medium, generating stronger DIB features. However, this does not necessarily mean the positive-velocity HV-DIB clump truly extends from 1 to 5 kpc as observed in Figure 12, since the asymmetric distribution of distance errors in Gaia can elongate structures along the line of sight and create artificial cloud shapes (Bailer-Jones et al. 2021).

Summary

In this paper, we analyzed the distance of the HVC ACS. We used interstellar extinction calculated from K-giant stars with LAMOST atmospheric parameters, 2MASS photometry, and Gaia distances, and employed the DIB feature at 5780 Å from LAMOST low-resolution spectra as our cloud tracers.

In both methods, the ACS signal is too weak to be detected. In the extinction method, we compared extinction variation between on-cloud and off-cloud stars, but no excess extinction was independently displayed. With the DIB method, it was possible to identify the cloud in velocity space. We should have discovered a component with anomalous line-of-sight velocity of about −100 km s^{-1} in the LSR if the ACS was within the detectable range of our O- and B-type star tracers. However, no prominent structure with negative velocity incompatible with the disk was found in the Galactic longitude-radial velocity plot.

Both analyses indicate that current data are still incapable of detecting the ACS. The most intuitive explanation is that the cloud lies beyond our tracers, allowing us to establish a distance lower limit of 8 kpc. Smoker et al. (2011) also measured the distance to the ACS using the absorption-line method. They had two tracer stars with ultraviolet band spectra, HDE 248894 and HD 256725, but also failed to identify absorption by the ACS, giving a lower limit of 8 kpc. The distances of HDE 248894 and HD 256725 can now be updated to 2.8 and 4.0 kpc from Bailer-Jones' distance estimation based on Gaia EDR3 (Bailer-Jones et al. 2021). Therefore, their lower limit should be revised to 4 kpc, and our work pushes the lower limit to 8 kpc, meaning the ACS might have a Galactocentric distance exceeding 16 kpc. Other explanations for our non-detection include: (1) the ACS signal may be concealed by strong Galactic disk contamination; (2) the neutral hydrogen and dust in the ACS may be insufficient to cause remarkable extinction excess.

Future directions for this study include improving the number, spatial scale, and measurement quality (accuracy/resolution) of stellar distances and obtaining deeper stellar spectrum observations. Additionally, we can investigate the physical nature of HVCs (e.g., their correlation with dust) to develop new detection methods.

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Facilities: Gaia, LAMOST.
Software: IPython (Pérez & Granger 2007), Jupyter (Kluyver et al. 2016), pandas (The pandas development team 2020), Astropy (Astropy Collaboration et al. 2022), numpy (Virtanen et al. 2020), matplotlib (Harris et al. 2020), scipy (Hunter 2007).

Appendix: Uncertainty Estimation of the Extinction Method

This section describes how we estimate uncertainties in the extinction method. The comprehensive uncertainty estimation includes uncertainty of the bluest edge, observational uncertainty of distance measurement, J-band and KS-band photometry, and Poisson error from binning data into sight lines and distance bins.

The Uncertainty of the Bluest Edge

The uncertainty of the blue edge comprises systematic uncertainty from metallicity and age variations of the star sample, and observational uncertainty. We examined the temperature-intrinsic color relation for K giants from PARSEC models (Bressan et al. 2012; Chen et al. 2014, 2015; Tang et al. 2014; Marigo et al. 2017; Pastorelli et al. 2019, 2020). Using PARSEC 1.2S isochrones with ages ranging from 2 to 13.7 Gyr (according to the star formation history of the Galactic disk from Nataf et al. 2024), metallicities from −1 to 0.5, and selecting stars at the Red Giant Branch stage, we found that broadening of the temperature-intrinsic color relation in the 2MASS J and KS bands due to age and metallicity variations is approximately 0.04 mag, providing an estimate of systematic error from these variations.

We also measured the bluest edge in different metallicity bins for our LAMOST DR5 K giants using a modified version of the method from Jian et al. (2017) and Cao et al. (2024). We binned stars by metallicity (width 0.15 dex, from −1.0 to 0.5 dex; except for the most metal-poor bin, which we set as −1.0 to −0.7 to ensure sufficient stars) and effective temperature Teff (width 50 K, excluding bins with fewer than 100 stars). To find the bluest edge, we iteratively selected the 5% bluest stars (by J − KS color) in each temperature bin, fitted their color-temperature relation using Random Forest Regressor, and removed outliers exceeding 3σ uncertainty (combining photometric uncertainties in J and KS bands and uncertainty from LAMOST effective temperature, 0.030 mag according to Jian et al. 2017). The resulting bluest edges for different metallicity bins are shown in Figures A1 and A2. However, observed variations in the bluest edge with metallicity were significantly larger than PARSEC model predictions: 0.1 mag versus 0.04 mag. According to Jian et al. (2017), this discrepancy likely arises from the choice of bluest star fraction, Poisson noise, and observational errors in photometry, temperature, and metallicity. Jian et al. (2017) estimated that different blue fractions introduce an error of about 0.02 mag.

We further estimated uncertainty in the blue edges from Poisson noise and observational errors in temperature and metallicity using Monte Carlo methods. Photometric and Teff values were recalculated 1000 times: each new value is the sum of the catalog value and a Gaussian random number determined by its observational error. We selected metallicity bins [−1.0, −0.7), [−0.55, −0.4), [−0.25, −0.1), and [0.35, 0.5) to represent uncertainty across different metallicity ranges. The resulting blue edge uncertainties are 0.0198, 0.0045, 0.0029, and 0.0051 mag on average across the Teff range, respectively. Note that for the [0.35, 0.5) bin, points with Teff < 4350 K were dropped due to insufficient star counts. Blue edges with Monte Carlo uncertainties are plotted in Figure A3. For the whole sample with metallicity in the range [−1.0, 0.5], Monte Carlo uncertainty is plotted in Figure A4, averaging only 0.002 mag.

Figure A5 compares the dispersion of the effective temperature-intrinsic color relation for RGB stars in PARSEC 1.2S with those computed for different metallicity bins. Overall, systematic error from the different blue fraction is 0.02 mag (Jian et al. 2017), and systematic error from age and metallicity variation is 0.04 mag (PARSEC). Uncertainties from Poisson and observational errors range from 0.003 to 0.020 mag when binning by metallicity, and 0.002 mag when using the whole sample. In the main text, we applied the bluest edge calculated from the whole sample with [Fe/H] ranging from −1.0 to 0.5, giving an overall bluest edge uncertainty of 0.045 mag.

The Uncertainty Caused by Observation and Poisson Error

For observational uncertainty in distance measurement, J-band and KS-band photometry, we accounted for these using Monte Carlo techniques to propagate uncertainties in observables to the final distance-extinction relation. The number of stars N in each distance and sight line bin also introduces Poisson statistical fluctuations, leading to additional uncertainty in mean extinction. However, in each Monte Carlo simulation, stars may be assigned to different bins due to observational errors, indirectly reflecting statistical fluctuations in star counts per bin (Poisson error). Therefore, we do not need to calculate this separately as it is already included in the simulation.

Similar to the previous section, distance, photometric, and Teff values of the bluest fraction were recalculated 1000 times via Monte Carlo: each new value is the sum of the catalog value and a Gaussian random number determined by its observational error. This yields 1000 realizations of the distance-extinction relation, from which we determine the 16th, 50th, and 84th percentiles. The overall uncertainty for each distance and sight line bin is calculated as:

$\sigma\{total\} = \surd(\sigma\{\mathrm{BluestEdge}\}^2 + \sigma\_\{\mathrm{MonteCarlo}\}^2)$

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References

Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., et al. 2022, ApJ, 935, 167
Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Demleitner, M., & Andrae, R. 2021, AJ, 161, 147
Bressan, A., Marigo, P., Girardi, L., et al. 2012, MNRAS, 427, 127
Cao, Z., Jiang, B., Wang, S., & Li, J. 2024, AJ, 168, 256
Chen, Y., Bressan, A., Girardi, L., et al. 2015, MNRAS, 452, 1068
Chen, Y., Girardi, L., Bressan, A., et al. 2014, MNRAS, 444, 2525
Clemens, D. P. 1985, ApJ, 295, 422
Cui, X.-Q., Zhao, Y.-H., Chu, Y.-Q., et al. 2012, RAA, 12, 1197
Davies, R. D. 1972, Natur, 237, 88
Draine, B. T. 2003, ARA&A, 41, 241
Ducati, J. R., Bevilacqua, C. M., Rembold, S. B., & Ribeiro, D. 2001, ApJ, 558, 309
Freudenreich, H. T., Berriman, G. B., Dwek, E., et al. 1994, ApJL, 429, L69
Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, Natur, 585, 357
Heiles, C. 1979, ApJ, 229, 533
Herbig, G. H. 1995, ARA&A, 33, 19

HI4PI Collaboration, Ben Bekhti, N., Flöer, L., et al. 2016, A&A, 594, A116
Hobbs, L. M., York, D. G., Thorburn, J. A., et al. 2009, ApJ, 705, 32
Hunter, J. D. 2007, CSE, 9, 90
Jian, M., Gao, S., Zhao, H., & Jiang, B. 2017, AJ, 153, 5
Kluyver, T., Ragan-Kelley, B., Pérez, F., et al. 2016, Jupyter Notebooks—a publishing format for reproducible computational workflows (Amsterdam: IOS Press), 87
Lan, T.-W., Ménard, B., & Zhu, G. 2015, MNRAS, 452, 3629
Lehner, N., & Howk, J. C. 2010, ApJ, 709, L138
Lehner, N., Howk, J. C., Marasco, A., & Fraternali, F. 2022, MNRAS, 513, 3228
Lehner, N., Keenan, F. P., & Sembach, K. R. 2001, MNRAS, 323, 904
Liu, C., Deng, L.-C., Carlin, J. L., et al. 2014, ApJ, 790, 110
Marasco, A., Fraternali, F., Lehner, N., & Howk, J. C. 2022, MNRAS, 515, 4176
Marigo, P., Girardi, L., Bressan, A., et al. 2017, ApJ, 835, 77
Muller, C. A., Oort, J. H., & Raimond, E. 1963, CRAS, 257, 1661
Nataf, D. M., Schlaufman, K. C., Reggiani, H., & Hahn, I. 2024, ApJ, 976, 87
Pastorelli, G., Marigo, P., Girardi, L., et al. 2019, MNRAS, 485, 5666
Pastorelli, G., Marigo, P., Girardi, L., et al. 2020, MNRAS, 498, 3283
Peek, J. E. G., Bordoloi, R., Sana, H., et al. 2016, ApJL, 828, L20
Pérez, F., & Granger, B. E. 2007, CSE, 9, 21
Ryans, R. S. I., Keenan, F. P., Sembach, K. R., & Davies, R. D. 1997, MNRAS, 289, 83
Schwarz, U. J., Wakker, B. P., & van Woerden, H. 1995, A&A, 302, 364
Sembach, K. R., Savage, B. D., Shull, J. M., et al. 2000, ApJL, 538, L31
Sembach, K. R., Wakker, B. P., Savage, B. D., et al. 2003, ApJS, 146, 165
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Smoker, J. V., Fox, A. J., & Keenan, F. P. 2011, MNRAS, 415, 1105
Smoker, J. V., Lynn, B. B., Christian, D. J., & Keenan, F. P. 2006, MNRAS, 370, 151
Tang, J., Bressan, A., Rosenfield, P., et al. 2014, MNRAS, 445, 4287
The pandas development team, 2020 pandas-dev/pandas: Pandas 1.0.3
Thom, C., Peek, J. E. G., Putman, M. E., et al. 2008, ApJ, 684, 364
Thom, C., Putman, M. E., Gibson, B. K., et al. 2006, ApJL, 638, L97
Tripp, T. M., & Song, L. 2012, ApJ, 746, 173
Verschuur, G. L. 1969, ApJ, 156, 771
Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, NatMe, 17, 261
Wakker, B. P. 1991, A&A, 250, 499
Wakker, B. P. 2001, ApJS, 136, 463
Wakker, B. P., & van Woerden, H. 1997, ARA&A, 35, 217
Wakker, B. P., York, D. G., Howk, J. C., et al. 2007, ApJL, 670, L113
Wakker, B. P., York, D. G., Wilhelm, R., et al. 2008, ApJ, 672, 298
Wang, S., & Chen, X. 2019, ApJ, 877, 116
Wang, S., & Jiang, B. W. 2014, ApJL, 788, L12
Wang, S., Zhang, C., Jiang, B., et al. 2020, A&A, 639, A72
Westmeier, T. 2018, MNRAS, 474, 289
Xiang, M., Rix, H.-W., Ting, Y.-S., et al. 2021, ApJS, 253, 22

Xu, Y., Hao, C. J., Liu, D. J., et al. 2023, ApJ, 947, 54
Xu, Y., Liu, C., Tian, H., et al. 2020, ApJ, 905, 6
Xue, M., Jiang, B. W., Gao, J., et al. 2016, ApJS, 224, 23
Yan, Q.-Z., Yang, J., Su, Y., et al. 2021, ApJ, 922, 8
Yan, Q.-Z., Zhang, B., Xu, Y., et al. 2019, A&A, 624, A6
Zhang, B., Liu, C., & Deng, L.-C. 2020, ApJS, 246, 9
Zhao, H., Schultheis, M., Recio-Blanco, A., et al. 2021, A&A, 645, A14
Zucker, C., Speagle, J. S., Schlafly, E. F., et al. 2019, ApJ, 879, 125

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