GALACTIC ALL-SKY SURVEY HIGH-VELOCITY CLOUDS IN THE REGION OF THE MAGELLANIC LEADING ARM

Bi-Qing For1, Lister Staveley-Smith1, and N. M. McClure-Griffiths2
1 International Centre for Radio Astronomy Research, University of Western Australia, 35 Stirling Hwy, Crawley, WA 6009, Australia; biqing.for@uwa.edu.au
2 Australia Telescope National Facility, CSIRO Astronomy and Space Science, PO Box 76, Epping, NSW 1710, Australia

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ABSTRACT
We present a catalog of high-velocity clouds in the region of the Magellanic Leading Arm. The catalog is based on neutral hydrogen (H\textsc{i}) observations from the Parkes Galactic All-Sky Survey. Excellent spectral resolution allows clouds with narrow-line components to be resolved. The total number of detected clouds is 419. We describe the method of cataloging and present the basic parameters of the clouds. We discuss the general distribution of the high-velocity clouds and classify the clouds based on their morphological type. The presence of a significant number of head–tail clouds and their distribution in the region is discussed in the context of Magellanic System simulations. We suggest that ram-pressure stripping is a more important factor than tidal forces for the morphology and formation of the Magellanic Leading Arm and that different environmental conditions might explain the morphological difference between the Magellanic Leading Arm and Magellanic Stream. We also discuss a newly identified population of clouds that forms the LA IV and a new diffuse bridge-like feature connecting the LA II and III complexes.

Key words: galaxies: interactions – Galaxy: halo – intergalactic medium – Magellanic Clouds

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Some atomic neutral hydrogen (H\textsc{i}) concentrations surrounding our Galaxy have anomalous velocities that are forbidden by a simple Galactic rotation model. These so-called anomalous-velocity clouds contain H\textsc{i} without a stellar counterpart. They can be classified into two velocity-based groups: intermediate-velocity clouds (IVCs; Münch & Zirin 1961; Blaauw & Tolbert 1966) and high-velocity clouds (HVCs; Muller et al. 1963). The classification of IVCs and HVCs is based on the deviation velocity, which is defined as the smallest difference between the velocity of the cloud and the Galactic rotational velocity (Wakker 1991). HVCs are particularly interesting because they are thought to represent the flow of baryons in or out of the Galactic disk, which influences the formation and evolution of our Galaxy. Despite being important in the context of galaxy formation and evolution, their origin and physical characteristics are still under debate.

Possible explanations of the origin of HVCs can be traced back to an early study by Oort (1966). One of his hypotheses suggested that the HVCs have an extragalactic origin. This hypothesis received more recent support from Blitz et al. (1999) with the argument that HVCs are dark matter dominated clouds in the Local Group with distances of hundreds of kiloparsecs. A similar study by Braun & Burton (1999) also claimed that compact and isolated HVCs lie at extragalactic distances. Another popular HVC origin hypothesis is the Galactic fountain model, in which the gas is blown out of the disk by supernovae, cools, and then rains back down (see, e.g., Houck & Bregman 1990). In this scenario, the fountain gas can rise as high as ∼10 kpc above the disk (de Avillez 2000).

The previous large-scale surveys, the Leiden–Argentina–Bonn Galactic H\textsc{i} survey (LAB; Kalberla et al. 2005) and the H\textsc{i} Parkes All-Sky Survey (HIPASS; Barnes et al. 2001), have provided opportunities to study HVCs on a global scale to assist in understanding their origin and physical properties (see, e.g., Wakker & van Woerden 1991; Putman et al. 2002). LAB covered the entire sky with an angular resolution of 36′ and a spectral resolution of 1.3 km s\(^{-1}\). HIPASS was conducted with a better angular resolution (16′) but lower spectral resolution (18 km s\(^{-1}\)). A comprehensive catalog of southern HVCs based on the HIPASS data was presented in Putman et al. (2002, hereafter P02). The catalog covers the high-velocity H\textsc{i} sky south of declination +2° and within the local standard of rest velocity (V\textsc{lsr}) range of +500 to −500 km s\(^{-1}\). It provides the spatial and kinematic distributions as well as the properties of HVCs. Even though the P02 catalog includes a complete census of HVCs south of declination +2°, the nature of the in-scan bandpass calibration technique filtered out some of the large-scale structure of the Milky Way and the Magellanic System.

Among HVC complexes, the Magellanic System is the most interesting given that it is the only closest extragalactic gaseous stream to our Galaxy. The Magellanic System consists of a coherent gas stream originating from the Magellanic Clouds (MCs), i.e., Magellanic Stream (MS) and Leading Arm (LA; Mathewson et al. 1974). The MS is trailing the MCs and has a complex filamentary structure. On the other hand, the LA is clumpy and dominated by three distinctive large complexes, namely, the LA I, LA II, and LA III (Putman et al. 1998; Brüns et al. 2005). An extended feature of the MS was recently discovered by Nidever et al. (2010), which reveals the total length of the MS as ∼200° across the sky. Another recent report of several filaments that are aligned with the MS also suggests that MS is wider than previously thought (Westmeier et al. 2012).

The formation of the MS and LA is generally believed to have been caused by the tidal interaction between the Milky Way and MCs. Theoretical models with tidal stripping and gravitational and hydrodynamical interactions can reproduce global observed H\textsc{i} column density and velocity distributions (see, e.g., Connors
et al. 2006; Mastropietro et al. 2005). However, these models do not provide a satisfactory explanation for the formation mechanism of the MS and LA. With the recent Hubble Space Telescope proper motion measurements of the MCs (Kallivayalil et al. 2006a, 2006b), a new unbound orbit for the MCs with a first passage scenario was proposed by Besla et al. (2007). The result is surprising given that the new orbit does not provide sufficient time for tidal and ram-pressure stripping mechanisms to produce the MS (Stanimirović et al. 2008). To circumvent the problem raised by the first passage scenario, Nidever et al. (2008) proposed a new blowout hypothesis. They suggested the supergiant shells in the dense southeast H region are blown out from the Large Magellanic Cloud (LMC) to larger radii where ram pressure and tidal forces can be easier to strip the gas and form the MS and LA. Nevertheless, with recent measurements of the Milky Way’s circular velocity (e.g., 251 km s$^{-1}$; Reid & Brunthaler 2004) that are higher when compared to the IAU standard of 220 km s$^{-1}$, there remains the distinct possibility that a multi-orbit scenario is plausible (Shattow & Loeb 2009). Recent multi-orbit simulations have also reproduced the observed structure of the MS, including the bifurcation of the two filaments, while remaining consistent with the proper motion data (Diaz & Bekki 2011, 2012). However, none of the theoretical models to date have been able to accurately reproduce the observed structure of the LA.

To study the Magellanic System in detail, Brüns et al. (2005) carried out a narrow-band Parkes H$\alpha$ survey. In contrast to HIPASS, which was not designed to accurately measure low-velocity Galactic H$_i$ gas, the survey was designed exclusively to study the Magellanic System. The Brüns’ survey has a similar angular resolution and spectral resolution to the Galactic All-Sky Survey (GASS; McClure-Griffiths et al. 2009; Kalberla et al. 2010; see Section 2), but with limited sky coverage. Another high-resolution H$\alpha$ study that concentrated on the northern tip of the MS was carried out by Stanimirović et al. (2008). This study was part of the Galactic studies with Arecibo L-band Feed Array.

The current work utilizes the GASS data for studying the general distribution and morphological types of HVC in the region of the Magellanic Leading Arm. The GASS data have better sky coverage than the Brüns’ survey and higher spectral resolution than HIPASS. The study of HVCs in the vicinity of the LA gives us clues to understand (1) the formation of the LA, (2) the physical properties of the HVCs, and most importantly (3) the role of infalling gas in the context of galaxy evolution and formation. In Section 2, we describe the GASS data and the procedures for cloud search algorithms. We present the catalog and the general distribution of clouds in Sections 3 and 4. Classification of the clouds and interpretation of the distribution for each group are given in Section 5. Finally, we report on the new extended features of the Magellanic Leading Arm and discuss the implications of HVCs for the formation and origin of the LA in Section 6. Conclusions are drawn in Section 7.

2. DATA

The neutral hydrogen data employed here are from GASS. This survey covers the entire southern sky to declination $+1^\circ$ and $V_{LSR}$ from $-400$ to $+500$ km s$^{-1}$. The data from the GASS second data release$^3$ have been corrected for stray radiation, have an angular resolution of $\sim16'$, a brightness temperature ($T_B$) sensitivity of 57 mK, a channel width of 0.82 km s$^{-1}$ and a spectral resolution of 1 km s$^{-1}$. For a typical HVC of 15 km s$^{-1}$ line width in our sample, the $\sigma$ H$\alpha$ column density ($N_{H\alpha}$) sensitivity is $3.5 \times 10^{17}$ cm$^{-2}$. We refer the reader to McClure-Griffiths et al. (2009) and Kalberla et al. (2010) for a detailed description of the observing technique and data reduction.

To create a catalog of HVCs in the region of the Magellanic Leading Arm, we extracted a GASS data cube within the area of $-30^\circ \lesssim b \lesssim +40$ and $240^\circ \lesssim l \lesssim 315^\circ$, and covered the velocity range of 0–450 km s$^{-1}$. Before performing any cloud search algorithm, we examined the data cube and determined the velocity range that solely contains Galactic H$\alpha$ emission, $0 \lesssim V_{LSR} < 150$ km s$^{-1}$. Beyond this velocity range, there is a mix of Galactic H$\alpha$ emission and possible H$\alpha$ emission that is associated with the MCs. Brüns et al. (2005) analyzed the HVCs in the region of the LA by using different velocity ranges within certain Galactic latitudes. Due to the difficulty in distinguishing the Galactic H$\alpha$ and H$\alpha$ emission originating from the MCs, we deliberately masked out the regions of $-20^\circ \lesssim b \lesssim +20^\circ$ and $l < 310^\circ$ between 150 and 190 km s$^{-1}$ for our analysis. Other small regions of Galactic H$\alpha$ emission in higher velocity channels, as determined by eye, were also masked. An integrated H$\alpha$ column density map of HVCs in the region of the LA over the velocity interval of 150–450 km s$^{-1}$ is shown in Figure 1.

2.1. Source Finding

We employed the source finding software, Duchamp$^4$, V1.1.13, developed by Whiting (2012). It is a three-dimensional source finding software that provides flexibility for the user to control all relevant input parameters. To enhance the detectability of fainter sources, it implements optional noise reduction techniques. Other small regions of Galactic H$\alpha$ emission in higher velocity channels, as determined by eye, were also masked. An integrated H$\alpha$ column density map of HVCs in the region of the LA over the velocity interval of 150–450 km s$^{-1}$ is shown in Figure 1.

1. Spectral channels with Milky Way emission, $0 \lesssim V_{LSR} < 150$ km s$^{-1}$, were flagged (see Section 2) and excluded when performing the search.
2. The cube was reconstructed via the à trous wavelet reconstruction method. It determined the amount of structures at various scales, and random noise was removed from the cube based on a user defined threshold.
3. We did not use the spectral or spatial smoothing to remove the random noise because tests had shown that the à trous wavelet reconstruction method yielded a better source detection rate.
4. A fixed threshold of $\sim2\sigma$ above the background noise (57 mK) was specified for the source finding. We did not adopt the auto-threshold determining scheme of Duchamp.
5. Duchamp searched for sources one channel at a time using the defined threshold. Sources were confirmed only if they extend to a minimum of 5 channels in velocity space and 10 pixels spatially.
6. Subsequently, detections were compared to earlier detected sources and either combined with a neighboring source or added to the list.

We also performed the source finding using Clumpfind. Clumpfind is a cloud finding algorithm developed to quantify the fragmentation or clumpiness of molecular clouds (Williams

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$^3$ http://www.astro.uni-bonn.de/hisurvey/gass/

$^4$ Available at http://www.atnf.csiro.au/computing/software/duchamp/.
Figure 1. Integrated H\textsubscript{i} column density map of GASS in the region of the Magellanic Leading Arm. The H\textsubscript{i} column density scale is 0 to $1.8 \times 10^{19}$ cm\textsuperscript{-2}. Locations of the Leading Arm complexes I, II, III and the Large Magellanic Cloud are labeled.

Table 1

| ID       | Designation | $V_{\text{LSR}}$ (km s\textsuperscript{-1}) | $V_{\text{GSR}}$ (km s\textsuperscript{-1}) | $V_{\text{LGSR}}$ (km s\textsuperscript{-1}) | FWHM (Jy km s\textsuperscript{-1}) | $T_{\text{B}}$ (K) | $N_{\text{H}_\text{i}}$ ($10^{19}$ cm\textsuperscript{-2}) | Semimajor (\degree) | Semiminor (\degree) | P.A. (\degree) | Flag | Classification |
|----------|-------------|------------------------------------------|-------------------------------------------|-------------------------------------------|-----------------------------------|-----------------|------------------------------------------|------------------|----------------|-------------|------|----------------|
| 66       | HVC+236.9−19.1+174 | ...                                      | ...                                       | ...                                       | ...                               | ...             | ...                                       | ...              | ...            | ...         | M    | ...            |
| 67       | HVC+307.2+26.8+174 | 174.0                                    | 17.5                                      | −60.2                                     | 12.4                              | 2.1             | 0.20                                      | 0.23             | 0.2            | −54         | ...  | HT            |
| 68       | HVC+273.5+24.5+174 | 174.2                                    | −25.6                                     | −79.9                                     | 4.3                               | 1.3             | 0.17                                      | 0.09             | 0.3            | 0.2         | 54   | ...            |
| 69       | HVC+251.3+36.6+175 | 174.5                                    | 7.3                                       | −28.0                                     | 48.0                              | 174.8           | 0.62                                      | 2.63             | ...            | ...         | IC   | ...            |
| 70       | HVC+293.3+19.1+175 | 174.8                                    | −16.2                                     | −85.5                                     | 11.5                              | 3.1             | 0.20                                      | 0.22             | 0.3            | 0.2         | 35   | ...            |
| 71       | HVC+313.9−01.7+175 | 175.2                                    | 16.8                                      | −54.0                                     | 8.7                               | 1.5             | 0.21                                      | 0.12             | 0.3            | 0.2         | −37  | ...            |

Notes.

\(a\) Corrected $F_{\text{int}}$.

\(b\) SR: the detection lies at the edge of the spectral region; M: the detection extends over to the masked Milky Way emission region; E: the detection is next to the spatial edge of the image.

\(c\) HT: head–tail cloud with velocity gradient; :HT: head–tail cloud without velocity gradient; S: symmetric cloud; B: bow-shock cloud; IC: irregular/complex cloud.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

et al. 1994). The routine contours the data with the user defined root mean square noise of the observations and interval, then searches for peaks of emission to locate the clumps at each contour level and splits any blended clumps with a friends-of-friends algorithm. We chose to adopt Duchamp for this study, as it breaks sources into fewer components.

3. CATALOG

We present the basic information for the sources in Table 1. The catalog includes the object identification number in Column 1; the designation with a prefix of HVC for high-velocity clouds and GLX for galaxies followed by the Galactic longitude, Galactic latitude, and the velocity in the local standard of rest reference frame ($V_{\text{LSR}}$) of the source in Column 2; $V_{\text{LSR}}$ in Column 3; the velocity in the galactic standard of rest reference frame ($V_{\text{GSR}}$), defined by $V_{\text{GSR}} = 220 \cos b \sin l + V_{\text{LSR}}$; the velocity in the Local Group standard of rest reference frame ($V_{\text{LGSR}}$), defined by $V_{\text{LGSR}} = V_{\text{GSR}} - 62 \cos l \cos b + 40 \sin l \cos b - 35 \sin b$ (Braun & Burton 1999) in Columns 5 and 6; velocity FWHM, measured at 50% of peak flux in Column 6; integrated flux, peak $T_{\text{B}}$, and peak $N_{\text{H}_\text{i}}$ in Columns 7--9; semimajor axis, semiminor axis, and position angle in Columns 10--12; warning flag in Column 13; and classification in Column 14 (see Section 5). Most of the parameters are derived from Duchamp, with the exception of the angular sizes and peak H\textsubscript{i} column density, which are determined independently. Sources that straddle...
our velocity boundary and masked Milky Way emission boundary are included in the catalog, but their physical parameters cannot be determined accurately and are therefore not listed in the table. We present examples of the integrated H\textsc{i} column density maps and LSR velocity maps of individual clouds in Figures 2 and 3.

With the procedures described in Section 2.1, we found 838 sources with Duchamp. False detections caused by background artifacts were eliminated from the initial search. The positions of final detected sources were subsequently examined using the NASA/IPAC Extragalactic Database with a 16' search radius to identify any galaxy. The final count includes a total of 419 HVCs and 12 galaxies in the region of the Magellanic Leading Arm. We determined the peak $N_{\text{H}\text{i}}$ by locating the brightest pixel in the integrated H\textsc{i} column density map of each source. To determine the angular size of the HVCs, we used two-dimensional Gaussian and elliptical fitting, which gave the semimajor axis, semiminor axis, and position angle. A detailed investigation and discussion of advantages and disadvantages for both fitting methods, applied to molecular cloud catalogs, is given in Kerton et al. (2003). We elect to use the results from the two-dimensional Gaussian fitting for the catalog. Due to the inaccuracy of the position angle in some cases, caution is needed when interpreting this parameter.

The reliability of Duchamp for the parameterization of sources has been extensively tested on artificial sources of various parameters by Westmeier et al. (2012). Their tests show that the integrated flux ($F_{\text{int}}$) measured by Duchamp is systematically
too low for faint sources. To demonstrate how this systematic error affects the integrated flux of real sources found in our catalog, we measured the $F_{\text{int}}$ with a better parameterization algorithm. This stand-alone parameterization algorithm uses the position output from Duchamp to find sources in the data cube. An integrated map is created and an ellipse fitted to the source. Subsequently, the ellipse grows in size until the measured integrated flux reaches a maximum. The $F_{\text{int}}$ is then measured within the final ellipse. In Figure 4, we show the ratios of our measured $F_{\text{int}}$ to $F'_{\text{int}}$ as measured by Duchamp as a function of measured $Duchamp F'_{\text{int}}$ in various bins. Parameterization of the large and extended or close kind of confused sources is challenging (T. Westmeier 2012, private communication). Thus, these sources are excluded from the comparison. The red, dotted line is a fit to the data points that represents the underestimated factor for a given $F'_{\text{int}}$ as measured by Duchamp. We conclude that Duchamp produces accurate measurements of $F'_{\text{int}}$ for sources with $F'_{\text{int}} \gtrsim 80$ Jy km s$^{-1}$ in our catalog. We correct all the $F'_{\text{int}}$ values measured by Duchamp based on the fitting function.

Corrections are not necessary for peak $T_B$ (fitted by Duchamp) and peak $N_{\text{HI}}$ (measured from the column density map). However, small systematic errors for of the order of 5%–10% of derived values may also be present in these parameters. The Duchamp determined velocity FWHM values, however, are generally very accurate (see Figure 8 of Westmeier et al. 2012). We will compare our catalog with the catalog compiled from a recent study by Venzmer et al. (2012, hereafter V12) in the Appendix.

Figure 3. Examples of velocity field maps of individual sources. Contours and colors representing the LSR velocity are shown. (A color version of this figure is available in the online journal.)
3.1. Comparison with P02 Catalog

Here, we compare our catalog to the P02 HVC catalog. The P02 catalog is based on HIPASS data, which have been reprocessed with the MINMED5 method to recover extended emission (Putman 2000). The catalog covers the entire sky in the declination range $-90^\circ$ to $+2^\circ$, and the velocity range of $+90\ \text{km s}^{-1} \lesssim |V_{\text{LSR}}| < +500\ \text{km s}^{-1}$. The $|V_{\text{LSR}}| < 90\ \text{km s}^{-1}$ limit does not exclude all of the emission associated with the Milky Way at low Galactic latitudes, and an additional deviation velocity constraint was applied to their selection criterion. The search was performed via an automated friends-of-friends HVC finding algorithm of de Heij et al. (2002).

In Figure 5, we show a comparison between HVCs from the P02 catalog that falls within our searched GASS survey volume and in our catalog. The total number of identified HVCs in this region is 419 for our catalog and 448 for the P02 catalog. We point out that our catalog includes 30 clouds which straddle our velocity boundary at $V_{\text{LSR}} = 150\ \text{km s}^{-1}$ and 71 clouds which extend over the boundary of masked Milky Way emission region. About 230 HVCs are identified as being in the same cloud in the two catalogs. The differences between the catalogs are due to: (1) degrees of breaking up or merging of clouds in extended complexes, for which Duchamp tends to merge clouds while the friends-of-friends algorithm employed by P02 tends to break up clouds; (2) the superior brightness sensitivity of HIPASS compared to GASS (9 mK per 15 km s$^{-1}$ compared with 15 mK per 15 km s$^{-1}$ in GASS), resulting in more faint sources to be detected in P02; (3) the excellent spectral resolution of GASS has allowed us to resolve narrow-line HVCs in the region, for which the spectral lines would have been smeared out in the case of a coarser spectral resolution of HIPASS; and (4) GASS has a better baseline coverage at the Galactic plane than HIPASS, resulting in more sources to be detected near the Galactic plane. We present a velocity FWHM distribution of both catalogs in Figure 6. HVCs that straddle our masked Milky Way emission boundaries and galaxies have been excluded in the plot. This figure shows that the majority

Figure 4. Ratio of “true” integrated flux ($F_{\text{int}}$) to the integrated flux ($F'_{\text{int}}$) measured by Duchamp as a function of $F'_{\text{int}}$. The red dotted line is the fit to the data points, which represents our estimated correction to the Duchamp values. (A color version of this figure is available in the online journal.)

Figure 5. On-sky distribution of the 431 sources detected by Duchamp (blue circles) and the 448 sources detected by Putman et al. (2002, red pluses) in the region of the Leading Arm. The integrated H\textsc{i} column density map of Figure 1 is shown. The sources from Putman et al. (2002) are within the same velocity range as the catalog presented in this paper. Comparison between the two catalogs is discussed in Section 3.1. (A color version of this figure is available in the online journal.)
of HVCs in the P02 catalog possesses larger velocity FWHM (30–35 km s$^{-1}$) than ours (10–25 km s$^{-1}$).

3.2. Completeness of the Catalog

We adopted the same method as described in Begum et al. (2010) to evaluate the completeness of our catalog. Ten fake clouds with various input parameters were injected into our data cube at random locations. The injected fake clouds were modeled with the Gaussian function. Input parameters of LSR velocity, peak $T_B$, velocity FWHM, position angle, and angular size in terms of semimajor and semiminor axes were randomly selected from various ranges. Ranges of input parameters were determined based on the cloud properties in our catalog.

We performed four sets of simulations with fake clouds being injected into the data cube between 150 km s$^{-1}$ and 450 km s$^{-1}$ LSR velocities.

1. Bright clouds with a narrow velocity line width: $T_B = 1.1–3.0$ K, velocity FWHM = 5–15 km s$^{-1}$, semimajor axis = 0.3–0.7, semiminor axis = 0.2–0.4.
2. Bright clouds with a broad velocity line width: $T_B = 1.1–3.0$ K, velocity FWHM = 16–30 km s$^{-1}$, semimajor axis = 0.5–1.0, semiminor axis = 0.2–0.4.
3. Faint clouds with a narrow velocity line width: $T_B = 0.14–1.0$ K, velocity FWHM = 5–15 km s$^{-1}$, semimajor axis = 0.3–0.7, semiminor axis = 0.2–0.4.
4. Faint clouds with a broad velocity line width: $T_B = 0.14–1.0$ K, velocity FWHM = 16–30 km s$^{-1}$, semimajor axis = 0.3–0.7, semiminor axis = 0.2–0.4.

Injected bright and faint clouds with a narrow velocity line width were fully recovered. The detection rates are 8/10 and 9/10 for faint and bright clouds with a broad velocity line width, respectively. The bright cloud with a broad velocity line width was missed because it was merged with another neighboring cloud. This is not uncommon considering that a cloud with a broader velocity line width has a higher chance of overlapping with another cloud in a crowded region, and hence merging into a larger cloud complex. Faint clouds with a broad velocity line width can be lost in the background noise. To summarize, it is likely that our catalog missed faint, broad velocity line width clouds, but Duchamp is relatively reliable for detecting narrow line width clouds for the studied region.

4. GENERAL DISTRIBUTION AND PROPERTIES

The integrated H I column density map of HVCs in the region of the LA shows a significant concentration of HVCs between Galactic longitude 240° to 260° and Galactic latitude −30° to +0° (see Figure 1 and Section 6). This population appears to be clumpy but has a few larger, more complex clouds (~3°–5° in angular size). Velocity field maps in the LSR and GSR reference frames, as shown in Figures 7 and 8, indicate large velocity gradients for the LA I and LA II complexes. Faint or thin filamentary structures of complex clouds are not visible in these maps but can be seen in the moment maps of individual sources (e.g., see Figures 2 and 3). We assume that all of these HVCs originated from the MCs and are associated with the LA due to their close proximity on the sky to the MCs and their similar range of velocities. The following statistical analysis excludes galaxies and objects otherwise flagged in the catalog.

We present the kinematic distributions of HVCs in $V_{LSR}$, $V_{GSR}$, and $V_{LGR}$ versus Galactic longitude and latitude in Figures 9 and 10, respectively. A comparison between HVCs in the P02 catalog (black dots) and ours (red dots) is also shown. The main difference is that our catalog only includes sources with $V_{LSR} > 150$ km s$^{-1}$. In the top panel of Figure 9, there are more positive than negative LSR velocity HVCs in the given Galactic longitude range. The overall velocity distribution of all P02 HVCs in Galactic and Local Group reference frames (middle and bottom panels of Figure 9) has a nearly equal number of HVCs with positive and negative velocities. The HVCs in our catalog are evenly distributed across the Galactic longitude between 240° and 320° in all reference frames.

The kinematic distributions of our HVCs in Galactic latitude are slightly different than for the HVCs in the P02 catalog. The top panel of Figure 10 shows the lack of identified clouds in the range of 150 km s$^{-1} < V_{LSR} < 190$ km s$^{-1}$ and −15° < $b$ < +15° in our catalog. The lack of clouds in this region is caused by the way we constructed the data cube, i.e., by deliberately masking out most of the emission in this velocity range to avoid any contamination from the Galactic H I emission (see Section 2). There is a lack of clouds at higher Galactic latitude as the velocity increases in all reference frames.

In Figure 11, we show histograms of $V_{LSR}$, $V_{GSR}$, and Galactic longitude and latitude (from top to bottom panels). The median $V_{LSR}$ and $V_{GSR}$ for the HVCs in the catalog are 232 km s$^{-1}$ and 42 km s$^{-1}$, respectively, which is consistent with the mean radial velocity of the LA (Brüns et al. 2005). We find that the number of clouds declines gradually as the $V_{LSR}$ increases above 200 km s$^{-1}$. Nearly the same number of clouds per 5° bin is found between Galactic longitude 250° and 300° (third panel). The total number of clouds below the Galactic plane outnumbers those above the Galactic plane, with a large fraction agglomerated between Galactic latitude −25° and −10° (bottom panel), where the region is closer to the LMC.
Figure 7. Velocity field map (first moment map) in the LSR velocity reference frame. The color bar represents the velocity range from 150 to 400 km s\(^{-1}\). The Leading Arm complexes and Large Magellanic Cloud are labeled.

(A color version of this figure is available in the online journal.)

Figure 8. Same as Figure 7, except in the GSR velocity reference frame with a velocity range from \(-200\) to \(+200\) km s\(^{-1}\).

(A color version of this figure is available in the online journal.)
Figure 9. Kinematic distributions of HVCs in the $V_{\text{LSR}}$, $V_{\text{GSR}}$, and $V_{\text{LGSR}}$ reference frames vs. Galactic longitude (from top to bottom). The black and red dots represent HVCs in P02 and our catalog, respectively. Excluded from the plot are: 30 clouds that extend below $V_{\text{LSR}} = 150 \, \text{km s}^{-1}$; 71 clouds that extend into the masked Milky Way emission boundary; 10 clouds that extend into the spatial edge of the image and galaxies. (A color version of this figure is available in the online journal.)

In Figure 12, we show the distribution function of the peak H$_{\text{i}}$ column density, which can be described by a power law: $f(N_{\text{H}_1}) \propto N_{\text{H}_1}^\alpha$. The distribution shows that high column density clouds are rare. The turnover at the low column density end of the distribution indicates that the population is limited by the survey sensitivity ($\sigma = 3.5 \times 10^{17} \, \text{cm}^{-2}$). A linear function was fitted in the log–log space and a negative slope of $-1.0$ was determined. This yields the final form of the distribution function as $f(N_{\text{H}_1}) \propto N_{\text{H}_1}^{-2.0}$. Comparing the distribution function of peak $N_{\text{H}_1}$ in the LA region with the MS (see Figure 10 of Putman et al. 2003), we find that both distributions turn over simultaneously at the low end of the column density, but the slope is steeper for their distribution function ($\alpha = -2.8$). This implies that clouds of all H$_{\text{i}}$ masses in the MS contribute significantly to the total H$_{\text{i}}$ mass of the Magellanic System.

5. HIGH-VELOCITY CLOUD MORPHOLOGICAL CLASSIFICATION

Different shapes of HVCs have been identified in the past; head–tail clouds in particular have been studied extensively (see, e.g., Brüns et al. 2000; Westmeier et al. 2005; Putman et al. 2011). Examining the integrated H$_{\text{i}}$ column density and velocity field maps of each cloud, we can classify the HVCs into five groups: (1) clouds with head–tail structure and with velocity gradient (HT); (2) clouds with head–tail structure but without velocity gradient (:HT); (3) bow–shock–shaped clouds (B); (4) symmetric clouds (S); and (5) irregular/complex clouds (IC). In Figure 13, we show the different morphological types of clouds in our catalog. An analysis of groups 1–4 is given in the following subsections.

5.1. Head–Tail Clouds

Traditionally, a head–tail cloud is defined as a cloud that appears to be cometary, with a compressed head trailed by a relatively diffuse tail and a visible clear column density gradient (Brüns et al. 2000). In this study, we find that some head–tail clouds consist of an additional clump of diffuse gas or have a kink in the tail, which is slightly more complex than the traditional head–tail clouds. This structure suggests that a fraction of the gas is being ripped off from the main condensation when it interacts with the surrounding halo gas.

Among the head–tail clouds, some show a velocity gradient, which is generally also associated with a column density gradient. Such a velocity gradient is another possible indicator for the detection of distortion caused by the interaction between clouds and an ambient medium (e.g., see PSM11; Brüns et al. 2000). Detection of a velocity gradient strongly depends on the spectral resolution of the data. Because of the high spectral resolution of GASS, in contrast to HIPASS, it is feasible to measure the velocity gradient in addition to the H$_{\text{i}}$ column...
density gradient when classifying head–tail clouds. We divide the head–tail clouds into two types (groups 1 and 2) and analyze them separately.

The total number of head–tail clouds is 100 (∼25% of the sample), with a typical head and tail column density that is different by a factor of five (typically ΔN_{HI} ∼ 4 \times 10^{18} \text{ cm}^{-2}). 60% (61/100) of the head–tail clouds show a clear velocity gradient. A wide range of velocity differences between the head and tail (∼5–25 km s\(^{-1}\)) is detected. We find that this particular group of head–tail clouds with a velocity gradient consists of two subgroups, with the velocity of the head either leading (pHT) or lagging (nHT) the tail. The numbers in the subgroups are about the same, 30 and 31, respectively.

In Figure 14, we show the peak H\(^{\text{i}}\) column density distributions of head–tail clouds with velocity gradient (top panel) and without velocity gradient (bottom panel) in the region of the LA. The pointing direction of the head–tail clouds is also presented, with the head and tail having been enlarged for better visibility. As discussed in Section 3, the accuracy of the position angle is subject to the fitting methods and complexity of the cloud shape. To better represent the pointing direction of the clouds, we visually inspected each head–tail cloud and manually adjusted the Gaussian fit position angle whenever necessary.

The head–tail clouds appear to be pointing in a random direction regardless of whether they belong to group 1 or group 2. In contrast, the study by PSM11 found that the majority of head–tail clouds in the region of the LA point in the general direction of the north Galactic pole, consistent with the general motion of the Magellanic System. The different conclusions may partly be due to the differences in selection criteria: (1) the velocity gradient is not well measured in PSM11; (2) only compact, isolated HVCs are searched for head–tail structure in PSM11; and (3) the selection of head–tail clouds is a subjective process. We have about a factor of two more head–tail clouds with velocity gradient than for PSM11 in the same region. The implication of this random motion for the formation of the LA and its interaction with the Galactic halo will be discussed in Section 6.2.

Examining the peak H\(^{\text{i}}\) column density distributions of both head–tail groups, we find that they populate the entire range of H\(^{\text{i}}\) column densities and are spread over the entire region. The distribution in V_{LSR} for both groups is shown in Figures 15 and 16, in which a dichotomy is found above and below the Galactic plane. Above the Galactic plane, a majority of the HT and :HT clouds possess V_{LSR} < 225 km s\(^{-1}\). Below the Galactic plane, it is populated by HT clouds with a wide range of V_{LSR}.

The distributions of peak H\(^{\text{i}}\) column density and velocity FWHM of these two head–tail groups as compared to the general population of HVCs in this study are presented in Figure 17. The black, blue and red histograms represent all HVCs, head–tail clouds with velocity gradient (HT) and head–tail clouds without
Figure 11. Histograms of $V_{\text{LSR}}$, $V_{\text{GSR}}$, Galactic longitude, and Galactic latitude of HVCs identified in the GASS data, from top to bottom, respectively. Excluded from the plot are 30 clouds that extend below $V_{\text{LSR}} = 150$ km s$^{-1}$, 71 clouds that extend into the masked Milky Way emission boundary, and 10 clouds that extend into the spatial edge of the image and galaxies.

Figure 12. Peak H$\text{I}$ column density distribution of HVCs in our catalog. A slope of $-1.0$ is derived from least-squares fitting of the data points above $10^{19}$ cm$^{-2}$ in the log–log plane, which corresponds to the distribution function, $f(N_{\text{HI}}) \propto N_{\text{HI}}^{-2.0}$. Excluded from the plot are 30 clouds that extend below $V_{\text{LSR}} = 150$ km s$^{-1}$, 71 clouds that extend into the masked Milky Way emission boundary, and 10 clouds that extend into the spatial edge of the image and galaxies.

Figure 13. Examples of cloud morphological types: (a) symmetric cloud, (b) bow-shock-shaped cloud, (c) head–tail cloud, and (d) complex and irregular cloud. (A color version of this figure is available in the online journal.)

18.4 < log ($N_{\text{HI}}$/cm$^{-2}$) < 18.6 (top panel). This result is different from the recent study by PSM11, where the majority of head–tail clouds possess log $N_{\text{HI}} > 19.0$. This is a factor of 2.5 higher in column density than those found in our sample. This is caused by the difference in the overall peak H$\text{I}$ column density distribution and number of detected narrow line width
clouds. The larger number of narrow velocity line width clouds in this study than P02 is not due to the false detections (see Section 3.2). Duchamp tends to merge clouds rather than breaking them into smaller clumps, which would result in a larger velocity line width for a merged cloud than smaller clumps. The peak H\textsc{i} column density distribution for :HT clouds is rather flat, most likely because of the small sample size. The velocity FWHM distributions are asymmetric with a peak at 22 km s\textsuperscript{-1} in all cases (bottom panel). Both velocity FWHM distributions of HT and :HT clouds extend out to \(~40\) km s\textsuperscript{-1}.

To analyze the two subgroups of head–tail clouds with velocity gradient (i.e., pHT and nHT), we plot them with different symbols in Figure 18. The plus and square symbols represent the pHT and nHT clouds, respectively. There are approximately equal numbers of pHT clouds and nHT clouds above and below the Galactic plane for both the peak H\textsc{i}
Figure 15. Top panel shows the sky distribution of identified head–tail clouds with velocity gradient (HT) in the region of the Leading Arm. The colors represent the $V_{\text{LSR}}$ of each head–tail cloud according to the color bar scale on the right side. The bottom two panels show the HT clouds superimposed on position–velocity maps. (A color version of this figure is available in the online journal.)

Columns density and $V_{\text{LSR}}$ distributions. As for the distribution of $V_{\text{LSR}}$ (bottom panel), pHT clouds possess slightly lower $V_{\text{LSR}}$ (<200 km s$^{-1}$) than nHT clouds (<250 km s$^{-1}$) above the Galactic plane. Below the Galactic plane, pHT clouds are evenly distributed across the range of $V_{\text{LSR}}$, and nHT clouds dominate at $V_{\text{LSR}} > 250$ km s$^{-1}$.

5.2. Symmetric and Bow-shock Clouds

The bow-shock-shaped cloud is characterized by a dense core with two deflected gas wings, which have a lower column density than the core. The presence of this type of cloud suggests ram-pressure interaction with the ambient medium. On the other
hand, symmetric clouds do not exhibit any morphological signs of disturbance. We note, however, that a head–tail cloud aligned with the major axis along the line of sight would also appear as a symmetric cloud.

In Figure 19, we show the distributions of symmetric (diamonds) and bow-shock-shaped (crosses) clouds in peak H$_1$ column density and $V_{LSR}$. There are only a few high H$_1$ column density ($>10^{18}$ cm$^{-2}$) symmetric clouds that are found above

**Figure 16.** Same as Figure 15, except showing head–tail clouds without velocity gradients. (A color version of this figure is available in the online journal.)
Figure 17. Histograms of peak H I column density (top panel) and velocity FWHM (bottom panel) of HVCs in this catalog. The black, blue, and red represent all HVCs, head–tail clouds with velocity gradient, and head–tail clouds without velocity gradient identified in GASS data, respectively. Only clouds with velocity FWHM less than 60 km s$^{-1}$ are being plotted in the histogram.

(A color version of this figure is available in the online journal.)
Figure 18. Sky distribution of head–tail clouds with positive velocity gradient (pHT; pluses) and with negative velocity gradient (nHT; squares). See definition in Section 5.1. The top and bottom panels show the distributions in peak H\textsc{i} column density and \(V_{\text{LSR}}\), respectively. The colors indicate the values according to the color bar scale on the right side.

(A color version of this figure is available in the online journal.)

the Galactic plane. Otherwise, they cover a wide range of \(N_{\text{H}}\) in the region of the LA. The majority of these clouds fall between 225 km s\(^{-1}\) and 340 km s\(^{-1}\) below the Galactic plane and less than 250 km s\(^{-1}\) above the Galactic plane. With a small sample of bow-shock-shaped clouds, we conclude that the typical bow-shock-shaped cloud has \(N_{\text{H}} \sim (0.2–1) \times 10^{19} \text{ cm}^{-2}\) and velocity less than 250 km s\(^{-1}\).

34% (23/69) of symmetric clouds also exhibit a velocity gradient. Velocity gradients in symmetric clouds can be caused by several effects. For example, there may be an angle between the HVC velocity vector and the line of sight, there could be rotation in the clouds, two or more HVCs could be superimposed on the same line of sight (Brüns et al. 2000), and there could be fluctuations in the background H\textsc{i} emission (Begum et al. 2010). There is no preferred direction for the velocity gradient for symmetric clouds in our catalog. We rule out projection of the LSR velocity as the cause of the velocity gradient. The typical velocity gradient is \(\sim 0.3–0.8 \text{ km s}^{-1} \text{ arcmin}^{-1}\), which is similar to the range \((0.5–1 \text{ km s}^{-1} \text{ arcmin}^{-1})\) found among the compact clouds studied by Begum et al. (2010). We note that our clouds are unresolved and thus subject to the effect of beam smearing.

6. DISCUSSION

6.1. Implications of LA Morphology for the Origin of the LA

With the large sky coverage of GASS, we have uncovered new extended features of the Magellanic Leading Arm. In
Figure 19. Same as Figure 18, except showing the sky distributions of symmetric (diamond) and bow-shock-shaped clouds (crosses).

(A color version of this figure is available in the online journal.)

Figure 20, we show the relative position of the LA I, LA II, and LA III (top figures) and individual LA complexes as identified by Duchamp (bottom subfigures). The red boxes highlight the extended features that were not detected in Brüns’ survey. The extended feature in LA I has been seen in other all-sky HVCs maps (see, e.g., Putman et al. 2002). It was not detected in the Brüns’ survey due to its longitude coverage cutoff at 310° near the LA I region.

The other extended feature seen in LA III is new. This feature consists of clumps connected by diffuse, low H I column density filaments. The most interesting part about this extended feature is what appears to be a “bridge” connecting the LA II (see the arrow in top figure). The velocity map of this extended feature also shows similar velocity between LA II and LA III near the “bridge.” This implies that LA II and LA III might have been part of a larger cloud complex in the past and have been pulled apart.

Here, we report a new population of clouds, named LA IV, that is located south of the Galactic plane and to the northwest of the LMC. Although LA IV has also recently been reported by V12, the defined boundary of LA IV is more extended in this study than in V12 (see the schematic diagram of the LA IV feature at the top right panel of Figure 20). The median $V_{LSR}$ of LA IV is $\sim 260$ km s$^{-1}$. The blue and dashed lines mark the estimated boundary and extended boundary of the population in the top left panel of Figure 20, respectively. The morphology
of LA IV is different from its counterparts, the LA I, II, and III complexes. It is formed by a stream of cloudlets rather than a large complex, the majority of which are head–tail and symmetric clouds, and span $\sim 50^\circ$ across the sky.

The origin of the LA is somewhat controversial. The overall velocity structure of the H I gas suggests that the LA originates from the LMC (Putman et al. 1998). The coincidence of the LA I position and morphology with the LMC southeast H I overdensity region further supports this observational evidence (Nidever et al. 2008). While metallicity measurements from HST spectra of background sources toward the MS and LA II only constrain their origin to the MCs ($Z = 0.2–0.4$ solar; Lu et al. 1994, 1998; Gibson et al. 2000), new measurements of FUSE and HST spectra suggest that they originate from the SMC (Sembach et al. 2001; Fox et al. 2010). This observational evidence is supported by various simulations (see Connors et al. 2006; Diaz & Bekki 2012).

If we ignore the controversy and assume that the LA has a single origin, then it does not explain why the LA IV has a different morphology than its counterparts. A possible explanation is that the LA IV has a different origin. In fact, the stream of cloudlets that form the LA IV appears to trace back to the LMC (see Figure 20). This explanation would fit the model scenario of SMC origin for the LA I, LA II, and LA III. Nevertheless, measurement of metallicity using background sources toward the LA IV and future simulations that incorporate the LA IV are necessary.

Distance must have an effect on the morphology because the H I gas can interact with different ambient medium in different regions of the Galactic halo. With the exception of the LMC and SMC distances (50 and 60 kpc, respectively), the distances to the LA and MS are hard to determine. According to the tidal models, the MS is further away from the Galactic plane than the MCs and the LA, with distances of 50–100 kpc at its tip (Yoshizawa & Noguchi 2003; Connors et al. 2006). An empirical study of the filaments near the tip of the MS estimated a distance of 70 kpc, which is in agreement with the tidal models (Stanimirović et al. 2008). The LA is at an approximate kinematic distance of 21 kpc (McClure-Griffiths et al. 2008), based on the evidence of the interaction between the LA I with the Galactic disk gas. This distance is smaller than the estimate due to the cloud disruption timescale, in which the gas stream from the MCs is not expected to reach the disk in the form of H I clouds (Heitsch & Putman 2009). Simulations also put the distance of the LA
at ∼50 kpc (see Figure 4 of Diaz & Bekki 2012), although the addition of ram-pressure stripping could result in a closer distance (Connors et al. 2006).

Examining the overall H\textsubscript{i} gaseous feature of the Magellanic System, we find that the global cloud morphology in the LA region is strikingly similar to the northern extension region of the MS (Nidever et al. 2008; Stanimirović et al. 2008). Both regions are rather clumpy and are populated with narrow line width clouds. These narrow line width clouds generally exhibit multiphase structure, which consists of a cold core surrounded by a warm envelope. The existence of such multiphase H\textsubscript{i} clouds along the northern tip of the MS, which is at a distance of 80 kpc, is rather surprising (Stanimirović et al. 2008). Further study of the physical properties of individual compact HVCs along the northern extension of the MS is needed to answer this question.

6.2. Implications of Head–Tail Clouds for the Formation of the LA

The morphology of HVCs provides an important clue in studying the interaction between the neutral hydrogen gas and the ambient medium in the Galactic halo. Head–tail clouds are a classic example of cloud disruption via ram-pressure stripping when moving through the halo medium. They are relatively common as compared to the other morphological types. Such an interaction commonly results in Kelvin–Holmholz and thermal instabilities, and ultimately cloud fragmentation and evaporation (Konz et al. 2002).

Parameters such as the cloud size and halo and cloud densities have been shown to govern cloud stability in three-dimensional hydrodynamical simulations (see, e.g., Heitsch & Putman 2009; Quilis & Moore 2001, hereafter HP09 and QM01, respectively). In the QM01 models, pure gas and extragalactic dark matter dominated HVCs with various gas densities, velocities, and temperatures were investigated. They found that a tail with \( N_{\text{HI}} \geq 10^{19} \text{ cm}^{-2} \) appears when the external medium exceeds the density of \( 10^{-2} \text{ cm}^{-3} \). Although a weak, faint tail with \( N_{\text{HI}} \sim 10^{18} \text{ cm}^{-2} \) also becomes visible when the density of the external medium reaches \( 2 \times 10^{-3} \text{ cm}^{-3} \). The setup of the HP09 simulations was slightly different from QM01. They took into account the heating by an ultraviolet radiation field and metallicity-based cooling mechanisms. Various halo density profiles, cloud masses, and velocities were tested for their wind-tunnel and free-fall models. The wind-tunnel model is best described as exposing the HVC to a wind with constant velocity and density. The free-fall model follows the trajectory of the HVC through an isothermal hydrostatic halo toward the disk. While both studies only consider clouds at lower \( z \) (within 10 kpc for the HP09 models), and hence might not be suitable to explain the formation and evolution of HVCs originating from the MCs, it is quite interesting to note that the simulations have successfully simulated prominent head–tail clouds even with kinks or multiple cores that are reminiscent of the observational structure of head–tail clouds in this study. The simulated timescale for the cloud disruption strongly depends on the physical conditions in the cloud and its interacting environment. Most head–tail clouds with high velocity are disrupted within 10 kpc and 100 Myr in the HP09 model, but tail disruption can last as long as \( \sim 10^7 \) yr in the QM01 model, after which the H\textsubscript{i} column density drops below the observational threshold.

The LA complexes are similar to head–tail clouds on a large scale. The directionality of their head and tail suggests that they are moving toward higher Galactic latitudes, although the curvature of LA II and LA III is in the opposite direction of LA I. The velocity gradient shows that the velocity at the head is slower than the tail in LA I and II (see Figure 7). This kind of velocity gradient is expected when the head of the cloud is decelerated while moving through the ambient medium.

Assuming that all small HVCs in the region of the LA (excluding cloudlets that form part of the LA IV) are fragments from the LA complexes due to cloud disruption, the directionality of the head–tail clouds should follow the direction of motion of the LA. However, this is not what we observed for the head–tail clouds either with or without the velocity gradient (as mentioned in Section 5.1; see also Figure 14). The pointing direction of the head–tail clouds is random, which suggests that turbulence in the medium must be at play. According to Audit & Hennebelle (2005), this scenario can be generated when the incoming warm neutral gas collides with the hotter ambient medium and creates a thermally unstable region. If the flow is weakly turbulent, then part of the warm gas condenses into cold gas, and any thermally unstable cold gas will continue to fragment until thermal equilibrium is achieved. In the case of a strongly turbulent incoming flow, which is the case for the interaction between the LA and the Milky Way halo medium (based on the velocity of the gas stream), the fragmented clouds should appear distorted and irregular. Strong turbulence also promotes the occurrence of fragmentation for the thermally unstable clouds, and subsequently, more small, cold clouds with lower density. This scenario appears to agree with the properties of HVCs in the region of the LA.

In Section 5.1, we presented the dichotomy in radial velocity for the head–tail and symmetric HVCs above and below the Galactic plane (see Figures 15 and 19), in which the HVCs below the Galactic plane possess lower \( V_{\text{LSR}} \) than above the Galactic plane. Such a dichotomy (or gradient as a function of Galactic latitude) is also seen in simulations, although the gradient is offset between the model and the observational data (see Figure 7 of Diaz & Bekki 2012). Simulations only include gravitational force, and we suggest that an orbital effect is the cause of such a dichotomy. Since we are only interested in the real distortion due to the interaction of the cloud with the ambient medium, we will only consider the head–tail clouds with velocity gradient for the rest of this discussion.

If we assume that all LA HVCs are traveling along the same orbit as the MCs, then we can use our knowledge of the MC’s total velocity and vector components to estimate the tangential velocity \( (V_t) \) of the HVCs from their measured radial velocities in the GSR frame. Hence, we can translate the median \( V_{\text{GSR}} \) of HT clouds above and below the Galactic plane into their associated tangential velocities \( (V_t) \) based on the relative fractions of the \( V_t \) and \( V_{\text{GSR}} \) of the MCs (LMC: \( V_t = 367 \text{ km s}^{-1}, V_{\text{GSR}} = 89 \text{ km s}^{-1} \); SMC: \( V_t = 301 \text{ km s}^{-1}, V_{\text{GSR}} = 23 \text{ km s}^{-1} \); Kallivayalil et al. 2006a). With the median \( V_{\text{GSR}} \) of \( -7 \) and \( 54 \text{ km s}^{-1} \) for clouds above and below the Galactic plane, the estimated tangential velocities are \( 270 \text{ km s}^{-1} \) and \( 330 \text{ km s}^{-1} \), respectively. While the \( V_t \) difference is small, we can estimate the mean density of the halo region \( (n_h(z)) \) that the clouds move through,

\[
C_D f_s n_h(z) = \frac{2N_{\text{HI}}g(z)}{v^2}
\]

(Benjamin & Danly 1997), where \( C_D \) is the drag coefficient, \( f_s = N_{\text{HI}}/(N_{\text{HI}} + N_{\text{HI}}) \) is the cloud neutral fraction, \( g(z) \) is the gravitational acceleration, \( N_{\text{HI}} \) is the total H\textsubscript{i} column density of the cloud, and \( v \) is the velocity of the cloud. We assume...
that the total H\textsc{i} column density of a typical head–tail cloud is $10^{19}$ cm$^{-2}$, the drag coefficient and cloud neutral fraction are 1.0, and the gravitational acceleration is constant ($0.2 \times 10^{-8}$ cm s$^{-2}$) beyond 10 kpc (Wolfire et al. 1995) for determining the mean halo densities. For velocities above and below the Galactic plane of 270 km s$^{-1}$ and 330 km s$^{-1}$, we obtain $n_h = 5.4 \times 10^{-3}$ and $3.7 \times 10^{-5}$ cm$^{-3}$, respectively. We note that the calculation is sensitive to the adopted cloud H\textsc{i} column density and uncertainty on $f_c$. Nevertheless, while the halo density is poorly known beyond 10 kpc, this exercise demonstrates that a slight difference in the halo density might cause the morphological differences between the LA I and LA II+LA III.

The presence of a large number of head–tail clouds in the region of the LA as compared to the MS is somewhat curious (see PSM11). A high angular resolution study of filaments near the northern tip of the MS has also shown the dominance of spherical clouds and an absence of elongated or head–tail clouds (Stanimirović et al. 2008). Assuming an isothermal halo, $P_{\text{ram}} \propto \rho v^2$, where $\rho$ is halo density and is proportional to $d^{-2}$, the distances predicted from the Diaz & Bekki (2012) simulations would suggest a higher ram-pressure interaction for the LA than the bulk of MS. Both observational evidence and theory support ram-pressure stripping as a more important factor than gravitational force for producing the morphological features of the LA. The inclusion of ram-pressure stripping in models could therefore result in closer predicted distances for the LA clouds, as suggested by the observational data. Finally, with the close distance of the LA, we suggest that fragmentation is not the only mechanism that produces the small clouds in the region. The cloud fragments with lower $z$-distances would experience increased background pressure, which would increase the cooling rate. This would result in the reforming of cold H\textsc{i} clouds, as seen under the free-fall model of HP09.

### 7. SUMMARY AND CONCLUSIONS

We have produced a catalog of HVCs in the region of the Magellanic Leading Arm from Parkes GASS data, using the cloud search algorithm Duchamp. We used Duchamp to parameterize cloud properties including position, velocity, and velocity FWHM. We determined the angular size of sources via two-dimensional Gaussian fitting and peak H\textsc{i} column density by searching the brightest pixel in the integrated maps. Comparison between our HVC catalog with that of Putman et al. (2002) in the same region and velocity range shows that the high spectral resolution of GASS allows us to recover clouds with narrow line widths. The total number of detected HVCs is 448 for the P02 catalog and 419 for our catalog. The combined catalog contains ~625 unique clouds.

We have presented the general distribution of HVCs in the catalog. The kinematic distributions with respect to Galactic longitude and latitude are generally consistent with the findings in P02. A trend of a decreasing number of clouds from higher to lower Galactic latitude as velocity increases in all velocity reference frames was found. A morphological classification of clouds was presented, and distributions of each type were discussed.

An extended feature in the LA I complex that was not covered in the detailed study of the Magellanic System by Brüns et al. (2005) was noted. A new population of clouds that forms the LA IV and an extended feature that forms a diffuse “bridge” connecting the LA II and III complexes were also discovered. The discovery of the LA III extended feature demonstrates the importance of brightness temperature sensitivity and spectral resolution for an all-sky survey. Simulations have yet to reproduce this feature of LA.

The most significant result in this study was the detection of a large number of head–tail clouds in the region of the LA as compared to the MS, suggesting that ram-pressure stripping is relatively more important than gravitational forces for the morphology and formation of the LA. The LA I and II themselves are large head–tail clouds, which are moving toward higher Galactic latitudes and both show a large velocity gradient, with the head being lower than the tail. We found that there was no preferred pointing direction for the small head–tail clouds. This suggests a scenario where the clouds are produced in a turbulent flow where incoming warm neutral gas collides with the hot halo interstellar medium (ISM). The cloud morphologies are strongly correlated to the degree of turbulence in the ISM. The presence of strong turbulence is probably the cause for the observed morphologies and properties of clouds in the region.

A dichotomy in velocity for the head–tail and symmetric HVCs above and below the Galactic plane was found. Since such dichotomy is also seen in simulations of Diaz & Bekki (2012), we suggest that an orbital effect is the cause. Finally, using the typical H\textsc{i} column density of cloud and tangential velocities above and below the Galactic plane, we infer a small difference in halo density. This suggests that the LA II and LA II+LA III are interacting with different halo environments, which might explain the morphological difference between them.

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### APPENDIX

### COMPARISON WITH V12 CATALOG

While this paper was under review, a similar study appeared in press by Venzmer et al. (2012). Here, we compare our catalog to the V12 catalog, which was compiled using a similar area of study to this paper. Venzmer et al. (2012) extracted the GASS data cube from 52 km s$^{-1}$ to 400 km s$^{-1}$ $V_{\text{LSR}}$ and performed the source finding and parameterization with the image processing software, ImageJ. We refer the reader to V12 for a detailed description of the source selection criteria. In Figure 21, we show a comparison between HVCs from the V12 catalog that fall within our studied area. The total of identified HVCs in this region is 419 (our catalog) versus 433 (V12). Sixteen of the HVCs in the V12 catalog lie outside our studied area.

While the total number of clouds between the two catalogs is similar, only ~120 HVCs are identified as the same cloud in the two catalogs. The differences are due to (1) degrees of breaking up or merging clouds in extended complexes, (2) the searched velocity range, and (3) selection criteria for clouds. The degrees of breaking up or merging clouds can be easily seen in Figure 21 (e.g., near the region of LA I), in which ImageJ breaks up more...
clouds than Duchamp for a given region. There are pros and cons for both source finding softwares in terms of degrees of breaking up or merging clouds. The advantage of breaking up a large cloud complex into smaller sub-clouds is that it allows for the analysis of individual sub-clouds (e.g., breaking up the LA I into LA 1.1–1.3). However, a high degree of breaking up of clouds can result in missed detections, such as the diffuse bridge-like feature we see connecting LA II and LA III.
As mentioned in Section 2, the Galactic H\textsubscript{I} emission is extremely strong in the velocity range 0 < V\textsubscript{LSR} < 150 km s\textsuperscript{-1}. Mild contamination is also evident between 150 and 190 km s\textsuperscript{-1}. Part of the searched velocity range in V\textsubscript{12} and this study is affected by Galactic H\textsubscript{I} emission. While we manually masked out the affected region, V\textsubscript{12} applied a cutoff to the velocity FWHM that excludes the Galactic H\textsubscript{I} emission. A comparison of velocity FWHM distributions in both catalogs in Figure 22 reveals a poor correlation. About 50% of the HVCs in the V\textsubscript{12} catalog have narrow line widths (defined here as velocity FWHM less than 10 km s\textsuperscript{-1}). Close examination of a subset of the V\textsubscript{12} narrow line width HVCs shows that some are real detection of small clumps, but some are false detections due to artifacts and noise peaks. Furthermore, there are a significant number of clouds with quoted velocity widths that are much lower than our measurement—in some cases as low as the GASS values of \(\sigma\).

We compare the velocity FWHM and peak \(N\textsubscript{H}\) values of HVCs that are found in both catalogs. HVCs identified as the same source in the two catalogs, but without listed parameters in our catalog, are excluded from the comparison. Figures 23 and 24 show the comparison of the measurements (top panels) and the difference in measurements (bottom panels). We find \(\langle\Delta V\textsubscript{FWHM}\rangle = -8.3 \text{ km s}^{-1}\), \(\sigma = 9.4 \text{ km s}^{-1}\), 85 HVCs; the velocity FWHM measured in V\textsubscript{12} is systematically lower than ours. The difference is more significant for broad line width HVCs (\(>20 \text{ km s}^{-1}\)). Direct comparison for the velocity FWHM of other small clumps as detected in V\textsubscript{12} cannot be made because they have been merged into larger clouds by Duchamp. Nevertheless, examining some of these HVCs in the GASS data cube, we find that the measurements in V\textsubscript{12} are consistently underestimated. For peak \(N\textsubscript{H}\), we find \(\langle\Delta N\textsubscript{H}\rangle = -0.25 \times 10^{19} \text{ cm}^{-2}\), \(\sigma = 0.91 \times 10^{19} \text{ km s}^{-1}\), 85 HVCs. The peak \(N\textsubscript{H}\) measurements in V\textsubscript{12} are also systematically lower than ours and with large differences for some of the HVCs.

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