

# Astro2020 Science White Paper

## High Velocity Clouds: Building blocks of the Local Group?

**Thematic Areas:**             Planetary Systems     Star and Planet Formation  
 Formation and Evolution of Compact Objects    Cosmology and Fundamental Physics  
     Stars and Stellar Evolution    Resolved Stellar Populations and their Environments  
    **X Galaxy Evolution**                       Multi-Messenger Astronomy and Astrophysics

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### Abstract (optional):

The gas reservoir in galaxies like the Milky Way can sustain star formation at its current rate for only  $\sim 1\text{-}2$  Gyr. For this reason and others, some low-metallicity inflow is required. High velocity clouds (HVCs) are the best candidates for that inflow. HVCs are gaseous objects with unusual velocities that lie in the halo of the Milky Way and can be used to trace important galactic processes, including the exchange of gas between disk and halo, accretion of new gas, and tidal streams. They thus occupy a critical position — spatially, temporally and kinematically — in the ongoing evolution of the Milky Way. Although HVCs were discovered in 1963, they are no longer curiosities; the community is working rapidly and over a broad scientific front to understand their role in galaxy evolution and how they connect galaxies to their surroundings. In the coming decade it will be possible to better illuminate the relationship between Galactic disks and their halos by determining the origin, properties and fate of HVCs in the Milky Way, and their analogs in nearby galaxies.

## I. Introduction

*Halo gas connects the baryon-rich intergalactic medium (IGM) to the star-forming disks of galaxies. It represents a galaxy's future star-formation fuel and the result of galactic feedback processes. (Putman+ 2012)*

The title of this white paper is identical — except for the question mark — to that of a provocative paper published in 1999 which suggested that the high-velocity clouds observed in 21cm HI emission to cover a very large fraction of the sky, are the baryonic component of gravitationally bound  $>10^8 M_{\odot}$  dark matter structures, located at a distance  $\sim 1$  Mpc (Blitz+ 1999). These days this model is thought to be inapplicable to the majority of high-velocity gas for the simple reason that every time an accurate distance to a high-velocity cloud (HVC) is measured, it is typically 1 - 50 kpc, not  $\sim 1$  Mpc (e.g., Putman+ 2012). Moreover, other galaxies have a population of extra-planar clouds that to first order resemble the Galactic HVCs and for M31 and M33 are confined to 50 kpc of those galaxies (Thilker+ 2004; Westmeier+ 2008; Grossi + 2008; Putman+ 2009, Miller+ 2009). Still, there is serious discussion about the possibility that least one prominent HVC has a large dark-matter component (Nichols+ 2014; Galyardt & Shelton 2016) and there are a few HVCs at a distance  $\sim 1$ Mpc (Wolfe+ 2016). Thus while HVCs largely remain a mystery, they appear crucial to our understanding of galactic evolution, and considerable observational and theoretical progress has been made. Here we will describe the diversity of the HVC phenomenon, stress their importance to critical questions in galactic evolution, and point out several promising directions for HVC research in 2020 and beyond.

This is a topic with an extensive history dating from Muller+ (1963), and has been the subject of conferences, monographs and reviews (e.g., Van Woerden+ 2004). In this short paper we regularly refer to the review by Putman+ (2012; hereafter P12) rather than to primary citations.

## 2. The High Velocity Sky – definition and properties

Figure 1 shows a map of HI emission whose velocity deviates by more than 90 km/s from what is expected at that location for gas rotating like the Milky Way disk (Wakker 2004). This, or a similar kinematic criterion, defines an HVC. Because the definition is based on radial velocities it is obvious that there must be a population of “low-velocity HVCs” whose peculiar motion is mostly transverse to the line of sight (Zheng+ 2015). A prominent feature of the high-velocity sky is the Magellanic Stream and its companion Leading Arm. This is the topic of a separate Decadal Survey White Paper by Fox+ and will not be further discussed here.

The gas in Fig.1 is just the tip of the iceberg: deeper 21cm surveys find a larger HI covering factor (Lockman+ 2002). Moreover, UV absorption line studies show that high-velocity gas at  $T \geq 10^5$  K covers  $\sim 80\%$  of the sky (Shull+ 2009; Richter+ 2017), and  $\sim 75\%$  of the UV-selected HVCs have  $N_{\text{HI}}$  below the  $\sim 3 \times 10^{18} \text{ cm}^{-2}$  limits of current all-sky 21cm HI surveys (Fox+ 2006; Lehner+ 2012). Many HVCs also show faint  $H\alpha$  emission consistent with photo-ionization from the Galactic radiation field, highlighting the role that HVCs play in the transport of energy between disk and halo (Bland-Hawthorn+ 1998; Haffner+ 2001; Barger+ 2012).

For many decades not a single HVC had a well-defined distance, but studies of HVCs in absorption against stars at different distances have finally removed the uncertainty for many

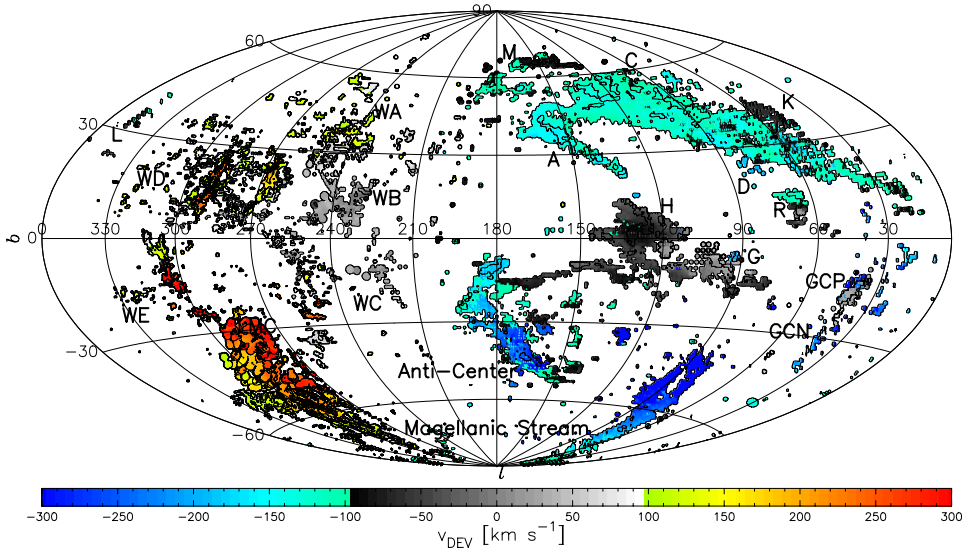


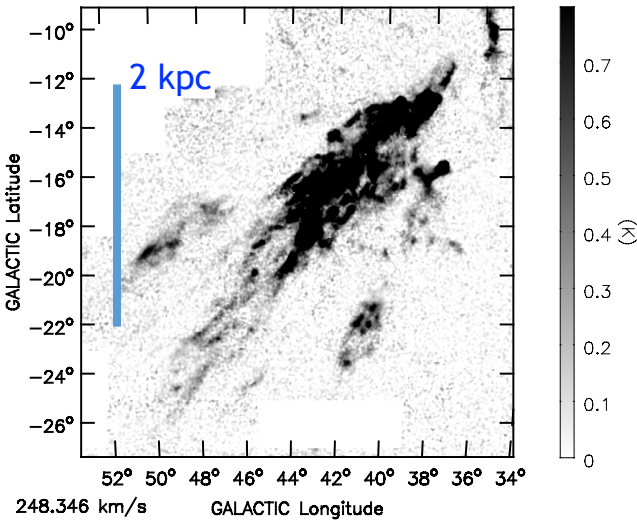
Fig. 1. The distribution of high velocity HI at  $N_{\text{HI}} > 3 \times 10^{18} \text{ cm}^{-2}$  (Wakker 2004). Colors show the velocity deviation from Galactic rotation. The Magellanic Clouds in the lower left are the origin of both the Magellanic Stream that extends to the right, and a “Leading Arm” that extends upwards to latitude  $30^\circ$  ahead of the Clouds.

clouds (e.g., Thom+ 2006; Wakker+2008; Lehner & Howk 2010). It appears that the “classic” HVCs (again, excepting gas associated with the Magellanic Clouds) are  $\approx 15$  kpc from the Sun, making the sum of their HI masses a few  $10^7 M_\odot$  (P12). Important facts about HVCs: 1) they do not contain stars (Hopp+ 2007); 2) their velocity is actually not that high: nowhere near the escape velocity of the Milky Way (Wakker 2004); 3) they have little dust and a low but not extremely low metallicity of 0.1-0.3 Solar (P12). 4) Some starless HVCs have been found in deep 21cm observations  $\sim 100$  kpc from M31 but not associated with any galaxy (Braun+ 2006; Wolfe+ 2013;2016); these would be undetectable in the surveys that produced Fig. 1.

### 3. The Origin of HVCs: Outflow or Infall

*There are, I think, only two interpretations to be seriously considered: (1) they result from a super-explosion somewhere in the galactic disk; (2) they result from inflow of gas from extragalactic space. Of these two, the first presents, on closer consideration of the quantities of gas involved, difficulties that seem well-nigh insurmountable. (Oort, 1969)*

It seems inevitable that HVCs are transitory features. They are over-dense for their location in the halo, so if they are pure gaseous structures they must be the recent product of either infall or outflow. Outflow and infall, which include galactic winds and galactic accretion, are vast topics, and place HVCs in a central location with regard to studies of galactic evolution. The modern consensus follows that of Oort (1969; e.g.,P12) with the added possibility that some HVCs might be gas stripped from dwarf galaxies. One HVC that is without question falling into the Milky Way and adding its mass to the disk is discussed next.



*Fig. 2: The Smith Cloud in a channel map of 21cm HI emission made with the Green Bank Telescope. The data suggest that it is moving to the upper right with components decelerating and mixing with the Milky Way.*

#### 4. The Smith Cloud

In the same year as the announcement of the discovery of HVCs, a short paper appeared: “A Peculiar Feature at longitude = 40.5°, latitude = -15°”. That paper does not mention Mueller+ (1963), but the

cloud Gail Smith discovered — the Smith Cloud — is one of the most interesting and highly-studied of all HVCs. After 55 years of investigation it is still not clear if it is typical or atypical.

A recent HI map of the Smith Cloud made with the Green Bank Telescope is shown in Figure 2. This is a slice at a single velocity, where the varying projection of the LSR across the Cloud has been removed. The central part of the Cloud extends over more than 15°, with additional components extending another 15° off the lower left of this map. The Smith Cloud is the most extreme example of the head-tail structure that is seen in some other HVCs (Bruns+ 2000). At its distance ~12 kpc its tip lies about 3 kpc below the Galactic plane, the projected size of its main section is 3x1 kpc and it contains several million solar masses of HI and probably an equal mass in H+ but no stars (Lockman+ 2008; Wakker+ 2008; Hill+2009; Stark+ 2015). Estimates of its trajectory have it moving to the upper right consistent with its morphology, with a total space velocity ~300 km/s, the largest component of which is in the direction of Galactic rotation. When it intersects the Galactic plane in ~30 Myr about 11 kpc from the Galactic Center, it will add angular momentum to the disk. A strong magnetic field has formed around the cloud from the compressed ambient interstellar field through which the Smith Cloud travels (Betti+ 2019). The inferred trajectory is shallow and implies that the cloud passed through the outer disk of the Milky Way ~70 Myr ago.

There are many puzzles surrounding the Smith Cloud, but two stand out, related to its origin. First, the estimated metallicity of the Smith Cloud toward three background AGN is ~0.5 Solar (Fox+ 2016). Thus the Cloud is not low-metallicity pristine material as might be expected if it was the product of a cold flow. Its gas has come from a galaxy of some sort. Second, the Smith Cloud is being shredded by its entry into the Milky Way. Models of a pure gas cloud on a trajectory anything like that of the Smith Cloud show that it cannot survive to its present location. Both puzzles may be resolved if the Cloud is imbedded in a large dark matter sub-halo that would stabilize it against disruption (Nichols & Bland-Hawthorn 2009; Nichols+ 2014). Moreover, if a dark matter sub-halo of about  $10^9 M_{\odot}$  passed through the outer Milky Way disk it would lose any gas it might have had, and might accrete Milky Way gas instead with about the observed metallicity, ~0.5 Solar (Galyardt & Shelton 2016; Gritton+ 2017).

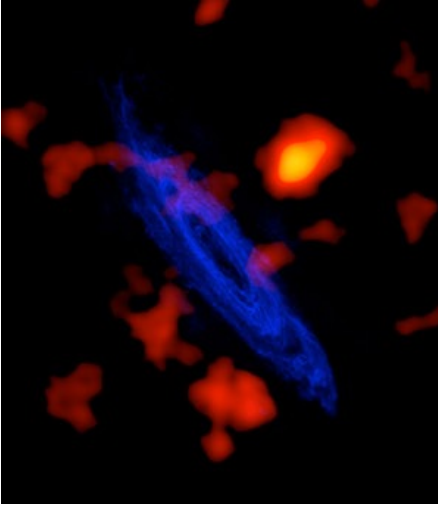


Fig. 3: HI in the galaxy M31 (blue) and its system of HVCs (red) from WSRT and GBT observations (Thilker+ 2004).

This invites the dizzying image of HVCs as a swarm of dark matter sub-halos passing through the disk, accreting gas from one location and depositing it in another. HVCs would then be not the building blocks of the Local Group envisioned in Blitz+ (1999), but nonetheless would be key to the evolution of individual galaxies. An alternative proposal that the Cloud is a product of supernovae in the Galactic disk (Marasco+ 2016) seems unlikely as it requires  $>10^{54}$  ergs of mechanical energy to move  $\sim 100$  times the HI mass of a large supershell (e.g., Pidpryhora+ 2007).

## 5. Steps Forward

As the most visible component of halo gas, HVCs present us with a treasure-trove of information about fundamental processes in galactic evolution. Several areas of study in the coming decade promise to answer questions fundamental to our understanding of galaxies like the Milky Way:

1. *Can theoretical magneto-hydrodynamic studies tie cold-flow accretion, or condensation from a galaxy's circumgalactic medium, or gas stripping from satellites, to the existence of a population of HVCs  $\approx 50$  kpc from the disk?*
2. *Do the HVCs contain enough mass to account for the chemical evolution history of the MW and to fuel future star formation?*
3. *How many, if any, HVCs contain dark matter?*
4. *Do metallicity maps of HVCs reveal their origin and show mixing with Milky Way gas as is already occurring in the Smith Cloud? Can abundance maps identify HVCs (besides the Magellanic Streams) that originated in the ISM of nearby dwarf galaxies?*
5. *How does the  $10^5$  K high-velocity gas relate to the HI and H $\alpha$  HVCs?*
6. *Do faint clouds like those found  $\sim 100$  kpc from M31 exist elsewhere in the Local Group? Are they remnants of the Group formation? Do they trace large dark-matter structures? Is there a Smith Cloud in M31? What is the HVC population around galaxies outside the Local Group?*

Research is required over a broad front of theoretical (Question 1) and observational areas (Q2-6). Wide-area HI maps to  $N_{\text{HI}} \sim 10^{17} \text{ cm}^{-2}$  obtained on large filled-aperture radio telescopes equipped with multi-pixel receivers are needed for Milky Way and Local Group studies (Q2,3,5,6). High angular resolution interferometers working to  $N_{\text{HI}} \sim 10^{18} \text{ cm}^{-2}$  will detect HI from distant HVCs and map accurate small-scale HI emission to derive more accurate metallicities (Q3, 4, 6). A proper census of HVC mass requires wide-field spectroscopic optical emission line studies capable of detecting H $\alpha$  emission measures  $\sim 0.1 \text{ pc cm}^{-6}$  at an angular resolution approaching that of the HI studies,  $\sim 10'$  (Q2,5). UV spectroscopy against background sources, like GAIA stars, is critical for abundance and excitation studies (Q4, 5) and will allow us to determine the 3-d structure of HVCs.

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