ONGOING GALACTIC ACCRETION: SIMULATIONS AND OBSERVATIONS OF CONDENSED GAS IN HOT HALOS

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ABSTRACT

Ongoing accretion onto galactic disks has been recently theorized to progress via the unstable interaction of the Galaxy and the Magellanic Clouds and outflows, etc.) that shape today’s galaxy population. HVCs have been known for over 40 years (Muller et al. 1963), having been first observed in the 21-cm hyperfine transition of neutral hydrogen. They are observed to be moving at hundreds of km s$^{-1}$, beyond what would be expected on the basis of Galactic rotation, with an overall sense of infall. Large maps have been made of the Galactic sky in HI (e.g. Putman et al. 2002, Kalberla et al. 2003), providing a good understanding of the gross observational characteristics of the HI HVCs. HVCs have also been observed in other atomic transitions (e.g. Sembach et al. 2003, Tripp et al. 2003), ionized gas (e.g. Putman et al. 2003, Tufte et al. 2002) and there are tentative detections of dust as well (Miville-Deschênes et al. 2005). These observations are much more sparse than the HI observations, and do not give us a sense of the distribution of the entire HVCs population, though they provide some useful fiducial characteristics, such as metallicity (van Woerden & Wakker 2004) and rough estimates of ionization fraction (Tufte 2004).

The origin and physical character of HVCs is still not known. The Magellanic Stream, a group of HVCs trailing the Magellanic Clouds, is certainly due to the interaction of the Galaxy and the Magellanic Clouds and may have come from some combination of ram-pressure stripping by the gaseous halo and tidal effects (Putman et al. 2003). Some Intermediate-Velocity Clouds (IVCs) have been shown to be very nearby (~1 kpc from the Galactic disk) and have near-solar metallicities, and are therefore thought to be part of a Galactic fountain, a formation scenario in which gas is kicked out of the disk and rains back down. The rest of the population of HVCs are thought either to be satellite debris akin to the Magellanic Stream or part of the cooling formation process. In the past both Galactic fountain models (e.g. de Avillez 2000) and Local Group models, wherein HVCs are dark-matter dominated clouds hundreds of kpcs from

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the Galaxy (e.g. Blitz et al. 1999), have also been invoked to explain HVCs. Neither of these models, though, is currently thought to be a successful explanation of the bulk of HVCs. Many HVCs have been shown to have distances beyond a few kpc (e.g. Thom et al. 2006, Wakker 2001), and low metallicities (for a review, van Woerden & Wakker 2004), which conflicts with the fountain model predictions of nearby, disk-like gas. Observations of Andromeda (Thilker et al. 2004, Westmeier et al. 2005) have excluded massive HVCs at great distances from that galaxy, which are a key prediction of Local Group models.

In an effort to understand the significance and scope of a Galactic gaseous halo, Sommer-Larsen (2006) (hereafter S-L06) ran numerical simulations of galaxy formation in the ΛCDM cosmology. These simulations showed that in Milky-Way-sized galaxies, significant baryonic mass resides in the hot halo. S-L06 also showed that infalling condensations are a natural consequence of such halos, and that it is possible to identify these clouds as HVCs.

In this paper we study the condensations found in S-L06 as HVCs and compare them to the HI HVC population in our Galaxy in terms of their number, flux and velocity distribution. We will also compare them to the HVC analogs observed around the Andromeda galaxy, which provides the opportunity to study the projected distance of HVCs, albeit with much lower resolution and sensitivity. We show that these condensations are indeed consistent with the overall HVC population and examine the simulation population for physical characteristics that may inform our future study of HVCs and ongoing galaxy formation.

2. OBSERVATIONS

2.1. Selecting HVCs from Galactic Observations

HVCs can be quantitatively defined in a variety of ways that reproduce the qualitative group of clouds traveling hundreds of km s$^{-1}$ relative to Galactic rotation. It is important to realize that as HVCs are defined by their radial velocities (redshifts), and that as such any scheme will undoubtedly misclassify some objects with high true velocity as slower moving gas. Local Standard of Rest (LSR) velocities (which is to say heliocentric radial velocities corrected for the Sun’s peculiar motion as compared to the mean motion of stars in the stellar vicinity) have been used historically to define the difference between HVCs and other Galactic clouds. Unfortunately, the rotation of the Galaxy will contaminate the sample of clouds, particularly towards (I = 90) and away from (I = 270) the direction of Galactic rotation. Classifying by Galactic Standard of Rest (GSR) velocities avoids some of these problems by moving into a frame at rest with respect to the Galaxy, but the disk gas contamination is still a strong function of angle on the sky, either requiring very harsh cuts ($v_{\text{GSR}} > 220$ km s$^{-1}$) or including a large amount of gas plainly part of the disk in the quadrants I and IV. A solution to this conundrum is the parameter $v_{\text{dev}}$, which is a measure of how the velocity of a cloud deviates from a relatively simple model of the Galactic disk. The model includes solid-body rotation in the Galactic center, a flat rotation curve at larger R and a flared disk (see Wakker 2004 for details). We use the criteria $|v_{\text{dev}}| > 60$ km s$^{-1}$ and $|v_{\text{LSR}}| > 90$ km s$^{-1}$, both to except the disk and to fulfill the classical definition of HVCs. These criteria are applied to observed and simulated HVCs alike. The $|v_{\text{LSR}}| > 90$ km s$^{-1}$ has a very limited effect upon the selected complexes once the $|v_{\text{dev}}| > 60$ km s$^{-1}$ is applied (it removes only one complex) and our results do not significantly depend upon whether the $|v_{\text{LSR}}| > 90$ km s$^{-1}$ is applied.

As we are interested in the global properties of HVCs rather than their minutiae, which are beyond the resolution of the simulation, we wish to use a full sky survey with consistent resolution and nomenclature. For this reason we use the updated Wakker and Van Woerden catalog (Wakker & Van Woerden 1991). This catalog has the velocities, fluxes and positions of more than 600 clouds; Wakker (2004) uses this same sample, and a more detailed description can be found therein. This catalog includes all clouds that have historically been catalogued as HVCs, and we exclude those clouds that do not fit our criteria for HVCs mentioned above. The 475 individual clouds that meet our criteria have an unweighted mean of -61 km s$^{-1}$ GSR and a standard deviation of 101 km s$^{-1}$ GSR.

Most of the HI flux of HVCs comes from HVC “complexes”: individual clouds that are members of a larger group of clouds in the same region of the sky with similar velocities. Clouds in the updated Wakker & Van Woerden catalog are labeled by the complex to which they belong, if any. There are independent clouds as well, but they make up a small fraction of the overall observed distribution.

The complex is the largest cohesive HVC grouping; we will use it as our fundamental unit for comparison to the simulation. We do not address the possibility that small, isolated clouds may be their own complex analogs at great distance. Indeed, if all such small clouds were distant complex analogs they should be reproduced by the simulation, and a comparison of small, isolated clouds would be fruitful. Many such observed clouds, though, may simply be physically small, nearby clouds. These nearby clouds would not be reproduced by the simulation, being below the simulation resolution limit, and would thus contaminate any comparison. We ignore them here for this reason.

Beyond excluding all small, isolated clouds from the comparison we also exclude complexes which have known, inconsistent origins. These are the “Outer Arm” complex, thought to be part of the warp of the Galactic disk; the “Magellanic Stream” and “Leading Arm” complexes, known to have originated in the Magellanic clouds; and all “Intermediate Velocity” clouds, which are thought to have come as an ensemble from the Galactic disk, owing to their high metallicity and proximity. Once we have eliminated irrelevant complexes, we are left with 14 HVC complexes.

2.2. HVCs around the Andromeda galaxy

In addition to Galactic observations of HVCs, analogs to HVCs have been discovered in other galaxies and, in particular, recent observations of Andromeda (M31) have shown a large number of distinct complexes (Thilker et al. 2004) (hereafter T04). The T04 observations are the most comprehensive study of extragalactic HVCs and have enough sensitivity to detect a large fraction of HVCs

| Parameter       | Value   |
|-----------------|---------|
| $v_{\text{GSR}}$ | > 220 km s$^{-1}$ |
| $v_{\text{LSR}}$ | > 90 km s$^{-1}$ |
| $v_{\text{dev}}$ | > 60 km s$^{-1}$ |
from the S-L06 simulations. These observations have an advantage over Galactic observations in that they have a projected galacto-centric radial distance for each cloud, as well as a relatively accurate distance and therefore HI mass for the clouds. At a distance of 775 kpc Andromeda is the nearest spiral galaxy to our own Milky Way. With a mass comparable to that of the Milky Way (Ségar et al. [2006]), and without evidence of recent major mergers, we expect Andromeda to have a relatively similar recent formation history, and therefore a similar population of HVCs, to our own Galaxy. The T04 observations cover a 94 kpc x 94 kpc square at Andromeda which, though smaller than the simulation domain, overlaps with the bulk of the simulated clouds. The resolution is 2 kpc with capacity to detect clouds down to a few $10^5 M_\odot$ of HI, depending upon their size, which is comparable to the mass resolution of the simulation. These observations (along with Westmeier et al. [2005]) show that there exists a significant population of HVCs within 50 kpc of Andromeda’s disk, with masses ranging from the sensitivity limit up to $10^7 M_\odot$, and that there are not HVCs with masses $\geq 10^6 M_\odot$ outside $R = 50$ kpc; these are significant constraints to which we can compare the simulations.

3. SIMULATIONS

The code used for the simulations is a significantly improved version of the TreeSPH code, which has been used previously for galaxy formation simulations (Sommer-Larsen et al. 2003). The main improvements over the previous version are: (1) The “conservative” entropy equation solving scheme suggested by Springel & Hernquist (2002) has been adopted. (2) Non-instantaneous gas recycling and chemical evolution, tracing 10 elements (H, He, C, N, O, Mg, Si, S, Ca and Fe), has been incorporated in the code following Lia et al. (2002a) and Lia et al. (2002b); the algorithm includes supernovae of type II and type Ia, and mass loss from stars of all masses. (3) Atomic radiative cooling depending both on the metal abundance of the gas and on the meta–galactic UV field, modeled after Haardt & Madau (1996) is invoked, as well as simplified treatment of radiative transfer, switching off the UV field where the gas becomes optically thick to Lyman limit photons on scales of $\sim 1$ kpc.

Sommer-Larsen (2006) selected a Milky-Way-like galaxy from a cosmological simulation and simulated its gaseous halo at extremely high resolution. The purpose of the experiment was to establish how large a mass fraction of the hot gas halos, shown to contribute significantly to the baryonic mass budget of such galaxies, condense into “warm” ($T \sim 10^4$ K) clouds by thermal instability. The result of the experiment was that only a few percent of the hot gas mass forms warm clouds; it was suggested that these clouds would be the equivalent of the HVCs. For the purpose of this paper, specifically addressing the properties of these warm clouds, an enlarged version of the above simulation was performed.

The base of the experiment was a $3.2 \times 10^5$ particle, fully cosmological simulation of a disk galaxy, which at $z=0$ has a characteristic circular velocity of $V_c=224$ km/s, very similar to that of the Milky Way. At $t=10.0$ Gyr ($z=0.3$), all gas particles within 250 kpc galacto-centric distance are split in eight particles of mass 1/8th the original value and gravity softening length (inverse gravity force resolution) 1/2 of the original value. The simulation is then continued for 200 Myr, and then all gas particles within 100 kpc galacto-centric distance are again split in eight particles of mass 1/8 and gravity softening length 1/2 of the previous values. At this point the simulation totals $1.1 \times 10^6$ particles, of which $8.6 \times 10^5$ are gas particles. The warm/hot gas in the inner 100 kpc of the galaxy halo is then resolved with particles of mass $m_{gas}=11700 M_\odot$ and gravity softening length 128 pc. As discussed by Sommer-Larsen (2006) this enables the simulation to resolve HVCs down to masses of $\sim 3 \times 10^3 M_\odot$ within 100 kpc galacto-centric distance. The (by now) very high resolution simulation is run for 500 Myr, until $t=10.7$ Gyr, at which point it was terminated due to the heavy computational load. By $t=10.3$ Gyr more than 100 potential HVCs have formed, with the number increasing slightly over the next 300 Myr. All HVCs are found at galacto-centric distances less than 100 kpc, no HVCs were found in the region $100 \leq r \leq 250$ kpc down to the mass resolution of $\sim 3 \times 10^3 M_\odot$ in this region of the halo (Sommer-Larsen 2006). We note that the necessary condition for onset of thermal instability, viz. $\tau_\chi < \tau_{cool}$, is satisfied everywhere in the hot halo gas ($\tau_\chi$ is the sound crossing time, which is taken to be $\sim 2 h_{SPH}/c_s$, where $h_{SPH}$ is the local SPH smoothing length and $c_s$ is the sound speed; $\tau_{cool} = E / E$ is the timescale for radiative cooling).

The bulk of the HVCs appear to have been seeded by remains from “cold accretion” events taking place much earlier in the history of the galaxy, as discussed by Sommer-Larsen (2006). However, given the much lower resolution of the main underlying galaxy simulation, starting at $z_i=39$ and running to $t=10.0$ Gyr, it is not possible to give a detailed discussion of the origin of the HVCs on the basis of the present simulations. These constraints also imply that the results obtained in this paper should, in general, be regarded as preliminary. Eventually, simulations starting at early times and of yet higher resolution should be undertaken, although such simulations are unfortunately computationally prohibitive at present.

3.1. Selecting individual HVCs from the simulation

We identified potential halo HVCs in three snapshots at 300, 400 and 600 Myr ($t=10.3, 10.4$ and 10.6 Gyr). First, all “seed” SPH particles in the halo, satisfying $n_H > n_{H, trig}$ and $T < 3 \times 10^4$ K, were identified. Second, a gas particle group finder was used to identify all SPH particles in coherent regions in the halo, surrounding these “seed” particles, and satisfying $n_H > n_{H, min}$. Third, only SPH particles in these regions satisfying $T < 3 \times 10^3$ K were retained. It is found that with $n_{H, trig} \approx 10^{-2}$ cm$^{-3}$ and $n_{H, min} \approx 10^{-3.5}$ cm$^{-3}$ one identifies neutral or partly photo-ionized $T \sim 1-3 \times 10^4$ K gas in HVCs and satellite galaxies (SPH particles in the coherent regions of $T > 3 \times 10^3$ K typically have $T > 10^5$ K and are almost fully photoionized), hence these density thresholds were adopted. Subsequently, the 7 satellite galaxies identified around this galaxy are removed on the basis of these systems containing (1) gas of high central density ($n_H \gtrsim 1-10$ cm$^{-3}$), (2) stars and (3) dark matter.

3.2. Physical characteristics of simulated HVCs
of HVCs in angle-velocity space, then the strong contrast
between many dozens of simulated and observable HVCs
and 14 observed complexes would convince us that the
simulation was not capturing the physical picture
correctly. In fact, it is visually evident that there is sig-
ificant clustering of HVCs in the simulation that either
were born as a single cloud and shattered or were created
in some coherent ‘cooling flow’. These clouds should be
treated as single entities, comparable to observed com-
plexes. To decide which simulated clouds should be as-
associated in this way we define a ‘distance measure’ in
position-velocity space between clouds:

\[ D = \sqrt{\Theta^2 + f^2 (\delta v)^2}. \]

Here, \( \Theta \) is the angular distance between two clouds, \( \delta v \) is
the difference in velocity between two clouds and \( f \) is a
conversion factor; \( f \) parameterizes the significance we as-
cribe to the angle subtended by two clouds versus their
difference in velocity in determining whether they are
members of the same complex. We choose \( f = 0.5 \, \text{km/s} \)
smoothly with the clustering in observed HVC complexes.
We place two clouds in the same com-
plex if their D is less than some number, \( D_0 \). A cloud
with no neighbors is considered a complex of its own.
The overall complex position and velocity are determined by
a flux-weighted average of the constituent clouds, consist-
tent with the method applied to the observed population.

This formulation leaves us with a free parameter, \( D_0 \).
As \( D_0 \) is increased the number of complexes decreases
roughly linearly for reasonable values of \( D_0 \), thus the
data do not offer a specific scale at which cloud clustering
takes place. We wish to choose \( D_0 \) such that we max-
imize the identification of true complexes and minimize the
identification of complexes that are the result of co-
incidental cloud superposition. To that end we scramble
all of the positions (l and b) and velocities (\( v_{\text{obs}} \)) of
the simulated clouds in each snapshot, such that all of the
coherent angular and velocity structures are lost, while
maintaining the distribution of each of these parameters
individually. We then run the clustering algorithm on
both the scrambled and unscrambled data sets for all
values of \( D_0 \). We assume that any complexes generated
in the scrambled data sets are spurious and we find the
average \( D_0 \) at which the difference in clustering, as pa-
parameterized by the number of complexes, is greatest be-
tween the true and scrambled data sets. This maximum
occurs at \( D_0 \approx 25^\circ \), with little variation across the three
snapshots. We adopt this value for generating simulated
cloud complexes hereafter.

4. ANALYSIS

4.1. Comparing Observed Milky Way and Simulated
HVCs

First we wish to compare the number and angular size
of observed HVC complexes to the simulated complexes.
Figure 4 shows each of the snapshots as observed from
the Sun along with the observed HVC data. The num-
ber of complexes is similar, \( 18.7 \pm 1.4, 22.6 \pm 2.6 \) and
\( 25 \pm 1.7 \) for the 300, 400 and 600 Myr snapshots respec-
tively, as compared to 14 in the updated Wakker and Van
Woerden catalog. While the numbers of simulated com-
plexes observed are very similar to observations, we do see
consistently more simulated complexes than observed

The three snapshots in the simulation (300, 400 and
600 Myrs) have 113, 128 and 130 identified HVCs, re-
spectively. Sommer-Larsen (2006) describes the mass
distribution of the clouds in the simulation, which is con-
sistent from snapshot to snapshot. HVC masses range from
\( 10^7 \, M_\odot \) to \( 5 \times 10^6 \, M_\odot \), with total masses ranging
from \( 8.8 \times 10^7 \, M_\odot \) to \( 10.7 \times 10^7 \, M_\odot \). Note that this total
mass is much lower than the \( \sim 2 \times 10^{10} \, M_\odot \) proposed in
MB04. Figure 1 shows the distribution of HVCs in the
three snapshots, indicating both masses and velocity vec-
tors. Note that the HVCs in each snapshot are not inde-
dependent; a typical cloud moving at 100 km s\(^{-1}\) will only
traverse 30 kpc from the first to last snapshot, so large
structures that are consistent from snapshot to snap-
shot may indeed be related. The cloud distributions are
roughly spherically symmetric and have an overall sense
of infall. Clouds tend to have velocity vectors similar to
their neighbors and show large-scale (\( \sim 30 \text{ kpc} \)) in-
flow structures. This is worthy of note as large, coherent
structures in HVCs are sometimes cited as qualitative
evidence of a satellite-accretion origin. Figure 2 shows
the number density and mass density profiles of each of
the snapshots. We note that the 300 Myr snapshot has a
noticeably lower number and mass density of clouds near
the disk. This effect is consistent with not enough time
having elapsed since the beginning of the highest reso-

tion simulation for the most massive clouds to have
formed and fallen into the center of the potential. The
400 Myr and 600 Myr snapshots have very similar density
structures, indicating a converged and continuous HVC
lifecycle.

In Figure 3 we plot the distribution of true-space veloc-
ity with respect to galactocentric radius of the HVCs for
each of the three snapshots. The most striking feature of
this plot is the increasing velocity of clouds with de-
creasing radius, consistent over time, which is also visible
in Figure 1. This should not be a terribly surprising re-



result, as clouds deeper in a galactic potential will typi-

ically have more kinetic energy, but the simple idea that more
distant clouds may have velocities that are less extreme
than other HVCs has not been much addressed in the
study of HVCs to date. Also evident in Figure 3 is that
at a given distance, more massive clouds typically move
faster. This effect consistent with the supposition that
drag from the gaseous halo on HVCs has a significant
kinematic effect, and that more massive clouds typically
have higher column densities.

3.3. Creating complexes from simulated HVCs

The contrast between the 14 observed complexes and
the 113, 128 and 130 simulated HVCs is not quite as great
as it seems because a large fraction of those simulated
HVCs would actually not be observably distinguishable
from disk gas. Low-Velocity Clouds (LVCs) or IVCs. If
we position a theoretical earth at \( R=8.5 \text{ kpc} \) within the
simulated disk and “observe” the radial velocities of these
clouds we can apply radial velocity cuts consistent with
HVC surveys. With these cuts, the number of clouds
that would be seen as HVCs are 54 ± 6, 63 ± 11 and
71 ± 8, respectively. The variability in this quantity, and
other “observed” quantities we investigate, comes from
the angle, \( \phi \), around the galaxy center at which the Sun
is positioned.

If in the simulation there were no clustering on the sky

Fig. 1.— The distribution of simulated HVCs in the three snapshots, showing HVC mass (left) and velocity (right). Each snapshot is projected onto the x-y and y-z planes, and shows a ring of radius 15 kpc centered in the galactic plane for scale and orientation. Symbol area scales with the mass of the clouds at left, and symbol length scales with the velocity at right.

We also wish to compare the velocities and fluxes of the simulated and observed HVCs. Fluxes are determined by assuming the gas in HVCs is 70% hydrogen by mass (consistent with Big Bang nucleosynthesis), and that the clouds are optically transparent to 21-cm radiation. This transparency assumption is reasonable as HVCs have a peak brightness temperature of a few K and a spin temperature upwards of 1000 K (see Kulikarni & Heiles (1988) for a discussion of the details of HI radiative transfer). Figure 6 shows the fluxes and velocities of each of the snapshots from four vantage points around the solar circle, along with the real HVC data. The total maximum HI flux in the simulated complexes are $3.2 \pm 1.3$, $7.8 \pm 3.6$ and $6.3 \pm 2.2 \times 10^5$ Jy km/s, as compared to $5.0 \times 10^5$ Jy km/s in the compared sample of real HVC complexes. Note that the maximum flux comes from the assumption that none of the cloud complexes, by 25% to 80%. This may be a preliminary indication that there exists variation in ionization fraction across complexes; if some complexes are completely ionized and some dominantly neutral, the number of HI-observable complexes would go down as compared with a consistent ionization fraction across clouds. The effect may also stem from the difficulty in discerning the difference between small complexes and isolated clouds: we discard isolated clouds from the observed data set, but include small complexes. It may be that it is difficult to draw that distinction in the updated Wakker & van Woerden (1991) data set. Some subtle evolution exists in the number of clouds and complexes in the simulation data, consistent with the halo requiring more than 300 Myrs to reach an equilibrium in the condensation of HVCs after the simulation has been run at high-resolution. Note that there are far more small clouds associated with a given complex in the real data, consistent with the limited resolution of the simulation. Also note that the simulated complexes have roughly similar angular distribution and size on the sky to those that are observed. In Figure 5 we show simulated complexes from four vantage points at the solar circle for each snapshot, demonstrating the variation in the distribution of complexes as a function of solar position.
is ionized, therefore if a large fraction (~70%) of the simulated HVCs were indeed ionized, simulation and observation would have significant discrepancy in HI flux. The range in total flux within a single snapshot is due to the fact that ~50% of the overall flux comes from just a few complexes closer than 10 kpc; as the observation point is rotated around the Galaxy, the distance to these complexes changes, changing the overall flux. This dependence upon only a few large, local clouds diminishes the usefulness of flux as a measure of the accuracy of the simulations. The average velocities (GSR) are also similar: \(-71 \pm 11, -82 \pm 16\) and \(-71 \pm 21\) km s\(^{-1}\), as compared to -68 km/s in the observed complex dataset. The standard deviation of the distribution of cloud velocities is 63 ± 9, 81 ± 12 and 81 ± 8 km s\(^{-1}\), as compared to 86 km/s in the observed complex data set. None of these distributions of observables contradict the hypothesis that the HVCs in the S-L06 simulations are analogous to the Milky Way’s population of HVCs.

4.2. Comparing Andromeda’s HVCs with simulated HVCs

We compare observed quantities in the T04 Andromeda dataset to our simulated data set. T04 find that there is \((3 - 4) \times 10^7 M_\odot\) in HI mass around Andromeda; we find 6.1, 7.5 and 6.8 \times 10^7 M_\odot in our 3 simulation snapshots of 300, 400 and 600 Myrs. This implies an ionization fraction ranging from 35% to 60% for the simulations to be consistent with the observations. The standard deviation of the projected velocities in the T04 Andromeda dataset is 126 km/s, although limiting the sample to objects with masses greater than \(5 \times 10^5 M_\odot\), where we expect the sample to be complete, reduces this to 96 km/s. Also note that this velocity dispersion only pertains to the qualitatively-defined “objects” in the dataset, which excludes diffuse gas closer to the Andromeda disk. The simulation snapshots, once projected to mimic the Andromeda viewing angle, have velocity standard deviations of 63, 71 and 89 km s\(^{-1}\).

The spatial distribution of the HVCs is one of the most interesting quantities to pursue in this comparison, as the Andromeda data set yields a minimum galactocentric distance for all observed clouds, a quantity not afforded by the Galactic data set. It is, unfortunately, a rather difficult quantity to extract, as the scale of distribution of the halo is very sensitive to the sensitivity of the observations to small clouds, which is difficult to accurately characterize in these observations. We can conclude that both the Andromeda data set and the simulation snapshots have detectable HVCs out to projected galactocentric radii of 50 kpc, and lack clouds with \(M > 10^6 M_\odot\) outside 50 kpc. A more detailed analysis of the scale-length and HVC density profile, including lower mass clouds, will have to wait for deeper, higher resolution...
where $M_0$ is the mass of a cloud, $v_i$ is a cloud velocity and $\hat{r}_i$ is the radial unit vector at the cloud. $n(R)$ is the number of clouds that exist in a spherical shell from $R - dR/2$ to $R + dR/2$. $\dot{M}(R)$ is not a well-defined metric within 10 kpc of the Galactic Center, as some of the HVCs will be removed from the system when they collide with the disk, so we exclude HVCs within 10 kpc from this analysis. We find that this HVC accretion rate, averaged over all three snapshots, can be easily fit by a line with $M(0) = 0.22 \pm 0.014 M_\odot$/year and $d\dot{M}(R)/dR = -2.5 \times 10^{-3} \pm 2 \times 10^{-4} M_\odot$/year/kpc. This disk accretion rate of 0.22 $M_\odot$/year is consistent with the assertion that HVC accretion is not the sole source of fuel for Galactic star formation (see Putman 2006 and Sommer-Larsen 2006). The monotonic increase in accretion rate with decreasing radius demonstrates that the cooling process that fuels HVC formation and growth operates at all radii within the halo.

5. DISCUSSION

5.1. The True Velocity Domain

The distribution that the simulated clouds present (see Figure 3) has a very clear variation of true velocity with galactocentric radius. Only one observed complex in the Galactic sky significantly strays from this region: the Magellanic Stream. This discrepancy, of course, does not contradict the hypothesis that the rest of the HVCs are generated by a mechanism similar to the one that generated the S-L06 HVCs; the Magellanic Stream was excluded from the analysis for the specific reason that is does have a well-known, non-cooling origin. The deviation of the Magellanic Stream from this area does indicate, however, that HVCs that are generated from satellite accretion may occupy a different part of the radius-velocity parameter space and that it therefore may be possible to distinguish the origin of an individual cloud if these values can be measured. Unfortunately, it is typically very difficult to measure cloud true velocity, or, equivalently, the angle that a cloud velocity vector makes with an observer-cloud vector, without strong model assumptions.

It is worth noting that the Very High-Velocity Cloud (VHVC) sub-complex that includes HVC 160.7-44.8-333 (annotated P07 in Figure 3) has been shown to have a galactocentric distance of $\sim 20$ kpc (Weiner et al. 2001; Peek et al. 2007). At a minimum velocity of 300 km s$^{-1}$, it is also marginally outside of the domain of clouds that are generated in the S-L06 simulations. Further distance limits on VHVCs may help to show whether these clouds are broadly inconsistent with cooling formation scenarios. Observations of VHVCs are particularly important as they have very large minimum true velocities, and are therefore plausibly excludable from the cooling-formation-origin domain. The vast majority, though, of the observed HVCs with distance constraints are consistent with the simulated HVCs.

5.2. HVCs at Low Velocity

A crucial byproduct of the analysis of simulated condensed clouds as observable HVCs is that fully half of all simulated clouds that have HVC physical characteristics would not satisfy the observational criteria for HVCs. Instead, these clouds would be construed as lower-velocity (and therefore nearby) gas. This is to say that if all HVCs are generated by processes similar to those in the S-L06 simulations we are ‘missing’ as many HVCs as we observe and thus underestimate the total scale of HVCs by a factor of two. This effect increases with greater radius - the average velocity of clouds decreases with radius (see Figure 3), such that more distant clouds will
be more often confused with local gas. The low apparent velocity clouds are startlingly asymmetrical. The ratio of the number of condensed clouds above $|b|$ of 50° with $-50 \text{ km s}^{-1} < V_{GSR} < 0 \text{ km s}^{-1}$ to clouds with $0 \text{ km s}^{-1} < V_{GSR} < 50 \text{ km s}^{-1}$ is $7 \pm 4$, $9 \pm 3$ and $11 \pm 3$ for each of the snapshots. If these clouds could be observationally deciphered from nearby LVCs, this asymmetry could be a powerful test of this model for HVC formation. It may be possible in the future to disentangle such clouds from local gas via their morphological characteristics, absorption to stars, low metallicity and very low dust-to-gas ratio.

5.3. CHVC hypotheses

Compact high-velocity clouds (CHVCs), are HVCs that are smaller than about 2° in projected size and are not associated with other HVCs in the sky. CHVCs have received significant attention in recent years (e.g. Braun & Burton 1999) under the assumption that some or all of them are analogous to the observed large complexes of HVCs but at much greater distances. Were this true, CHVCs could dominate the mass of Galactic HVCs, and would be very important to understanding the structure of the HVCs and the Galactic halo. This assumption hinges on the relative homogeneity of HVCs across distance. If HVCs have a distribution similar to the simulated distribution, this assumption would prove false. The most massive HVCs in the S-L06 simulations are typically closest to the disk, and they do not have analogs 50 to 100 kpc from the galaxy. In addition to this, the simulated velocity distribution of local HVCs is not analogous to that of distant HVCs; distant HVCs move slower, thus if some CHVCs are indeed distant objects (and the cooling-formation predictions are correct) there will exist a trend toward lower velocities in CHVCs. CHVC catalogs do not show a lower velocity dispersion than catalogs of HVCs (Putman et al. 2002), but such a discrepancy may be hard to detect as small,
local clouds may masquerade as distant CHVCs (thus polluting the sample; see discussion in Section 2.1) and disk gas may obscure a large fraction of the population of slow-moving, distant CHVCs. Conversely, it is possible to limit the contribution to the HVC population from cooling-formation HVCs if tiny HVCs with $V_{\text{GSR}} > 200$ km s$^{-1}$ can be shown to be distant ($R > 50$ kpc).

6. CONCLUSION

The distributions of complexes in terms of their velocity and flux in the S-L06 simulations are consistent with HVC observations of the Milky Way and Andromeda, and point to neutral fractions above $\sim 30\%$. The neutral fraction implied by the Andromeda comparison is consistent with the neutral fraction implied by the Milky Way HVC comparison. This lower limit discredits a “tip-of-the-iceberg” picture of HVCs, wherein HVCs are dominantly an ionized phenomenon and the observed HI is just a small fraction of the baryonic mass of the clouds. The number of simulated complexes and their angular distribution on the sky is also consistent with the Milky Way HVCs, when the velocity selection effects and clustering effects are taken into account. The radial distribution of clouds is consistent with the Andromeda sample and, in particular, the lack of massive ($\sim 10^6 M_\odot$) clouds at large radii (> 40 kpc) in the simulation is consistent with observations of Andromeda which show a dearth of such clouds far from the disk. The physical and observational population characteristics of the simulated HVCs are consistent over 300 Myrs (excepting the nearest, most massive HVCs in the first snapshot) and are broadly independent of the point of observation chosen on the solar circle. We have shown that material condenses into HVCs from $R = 10$ kpc to $R = 100$ kpc in the halo, and that the HVCs have an overall accretion rate of $\sim 0.2 M_\odot$/ year.

We have also shown that the velocity-distance domain is populated by simulated HVCs only in a specific region, and that all HVCs with known distances and unknown origins reside in this region. This points to a possible method for discriminating HVC origin given true space velocities. The simulated clouds would not always be identifiable as HVCs, as they may have low projected velocity. We find $\sim 50\%$ of these halo clouds do not show high enough projected velocities to be considered HVCs. Distant simulated HVCs are typically less massive and slower moving than nearby simulated HVCs, implying a different distribution of physical parameters for distant CHVCs than for the nearby HVC population.

Observations using the Arecibo L-Band Feed Array will refine our understanding of both the Galactic HVC population with the GALFA-HI observing program (e.g. Peek et al. 2007 and Stanimirović et al. 2000) and the distribution of HVCs around other galaxies with the AGES observing program (e.g. Auld et al. 2006). Instruments coming online now, such as the Allen Telescope Array, will allow us to map the HI HVCs in the vicinity of other nearby galaxies with unprecedented efficiency and further compare these cooling-formation simulations to observed systems. In this way we may be able to determine whether there are characteristics of extra-galactic HVC systems that can inform our understanding of the formation of these galaxies and the variation in the character of their baryonic halos. In the more distant future, the Square Kilometer Array will allow us to extend this analysis to non-zero redshift, probing the cooling history of galaxies into the age of mergers.

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Fig. 6.— Twelve plots of GSR velocity versus HI flux for simulated HVC complexes and observed HVC complexes. In each plot the observed HVC complexes are depicted by gray filled circles for comparison. The dashes represent simulated complexes, with the right side of the dash representing 50% ionization and the left side of the dash representing 0% ionization. From left to right the plots are of 300, 400 and 600 Myrs into the simulation. From top to bottom the plots represent viewpoints of $0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$ around the solar circle.
