HIGH VELOCITY CLOUDS: THE MISSING LINK?

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Abstract. Hierarchical structure formation models predict the existence of large numbers of low velocity dispersion dark halos. Galaxy surveys find far fewer galaxies than predicted by analytical estimates and numerical simulations. In this paper, we suggest that these dark halos are not missing, but have been merely misplaced in the galactic astronomy section of the journals: they are the High Velocity Clouds (HVCs). We review the predictions of our model for the Local Group origin of the HVCs and its implications for the formation and the evolution of our Galaxy. We describe recent observations that confirm many of earlier predictions and discuss future tests of the model.

1. The Missing Galaxy Problem

A generic prediction of hierarchical structure formation models is the existence of large numbers of low mass halos. The Press-Schechter formalism (Press & Schechter 1974) predicts that the galaxy mass function,

\[ n(M) \propto M^\alpha \exp(-M/M_*) \]

has a steep faint end slope, \( \alpha \simeq -2 \). Numerical simulations (Efstathiou et al. 1988; Gelb & Bertschinger 1994, Klypin et al. 1999) are consistent with the Press-Schechter approach: they also predict copious low mass halos.
Most galaxy surveys, however, do not seem to find large numbers of low luminosity, low velocity dispersion galaxies. Loveday (1998) summarizes a number of recent field surveys that find a faint end slope in the range $-1.2 \simeq \alpha \simeq -0.7$. Groups have similar “flat” galaxy luminosity functions with slopes typically $\sim -1$ (Muriel, Valotto & Lambas 1998). While surveys that reach lower surface brightness limits find more dwarf galaxies (Bothun, Impey & McGaugh 1997, Dalcanton et al. 1998), even the inclusion of these systems does not appear to increase the faint end slope enough to reconcile theory and observation.

In our own Local Group, where the galaxy inventory is thought to be essentially complete, the discrepancy is even more severe. Simulations at the appropriate scale suggest that the Local Group should contain roughly 1000 objects with velocity dispersions larger than 10 km s$^{-1}$ (Klypin et al. 1999). Observers however have only been able to find $\sim 30$ galaxies in the Local Group (Mateo 1998).

Where are the missing dark halos? There is either something wrong with hierarchical structure formation, the numerical simulations, or there are a host of unidentified bound systems in the Local Group.

What are the likely properties of these low velocity dispersion halos? Star formation is likely to be inefficient in these low luminosity systems because the cosmological ultraviolet background can prevent or at least delay the formation of atomic and molecular hydrogen (Babul & Rees 1992; Kepner, Babul & Spergel 1997; Barkana & Loeb 1999). If these missing galaxies have not formed stars, they likely persist as small bound objects containing mostly ionized hydrogen and possibly a handful of stars. These dark halos may be the High Velocity Clouds (HVCs).

The HVCs are clouds of atomic hydrogen detected primarily by means of their 21-cm emission that cannot be in circular rotation about the Galactic Center. Because they are largely found at high Galactic latitude, and because the HI layer of the Milky Way is so thin, the characteristic distance to the HVCs can, in principle, be anywhere between several hundred parsecs and 1 Mpc. In this paper, we will argue that the evidence points to a Local Group origin for the HVCs. Oort’s (1964) original idea that the clouds represent infall onto the Milky Way was abandoned long ago because of the discovery of HVCs with positive galactocentric velocities. Nevertheless, we will argue that his insight that the HVCs represent the unaccreted remnants of galaxy formation is largely correct. We will also offer some speculations on the implications of the Local Group origin. A fuller, more detailed account of the arguments presented in this paper may be found in Blitz et al. (1999a). Some of the arguments in this article have already appeared as Blitz et al. (1999b).
2. Evidence for a Local Group Origin

2.1. KINEMATIC DATA

The flux from HVCs is less than $10^{-4}$ of the normal Galactic emission. In the outermost parts of the Milky Way, a longitude-velocity plot of the normal Galactic emission shows that the contours are very nearly sinusoidal. The radial velocity, $v_r$, of the gas in circular orbit around the center obeys:

$$v_r = \Theta \left( \frac{R}{RO} - 1 \right) \sin l \cos b$$

where $\Theta$ is the circular velocity of a gas parcel at a distance $R$ from the Galactic Center, and where $R_O$ is the distance of the Sun from the Center. Thus, for gas close to the plane ($\cos b \approx 1$), sinusoidal profiles for a flat rotation curve are indicative of gas at constant radius. Conversely, the galactocentric distance of gas along a sinusoid can be inferred from its maximum velocity ($\sin l \cos b = 1$). Longitude-velocity plots from the Leiden-Dwingeloo survey (Hartmann & Burton 1997) exhibit HI emission with maximum velocities of about $\pm 170$ km s$^{-1}$ (Blitz et al. 1999), implying that for a flat rotation curve, the HI disk of the Milky Way extends to a distance of $\approx 37$ kpc from the Galactic Center.

Although most of the HVCs are far from the Galactic plane, one large cloud known as Complex H (after Aad Hulsbosch who has spent years observing and categorizing the HVCs), lies directly in the plane and is shown in Figure 1. The velocity centroid of this cloud is $-194$ km s$^{-1}$. If it were within the HI disk, the velocity difference between this cloud and the gas in normal galactic rotation would be between 30–200 km s$^{-1}$ giving rise to a very large region of highly shocked gas with an energy of $\approx 10^{54}$ ergs, nearly independent of distance over a large portion of the disk. This much energy would give rise to a region of disturbed gas in the HI disk at least 25 degrees in extent as well as giving rise to strong H$\alpha$ and perhaps x-ray emission, but none of these is evident. Cloud H must therefore lie beyond the HI disk at a distance of at least 40 kpc from the center. If it is at a distance of 50 kpc, the cloud has a diameter of 20 kpc, and an HI mass of $9 \times 10^7 M_\odot$, a huge HI cloud comparable in mass to a dwarf spheroidal galaxy. If this cloud is typical of the others, then the typical distance of the HVCs will be $\approx 25$ times larger (since the median angular size of the HVCs is $\approx 25$ times smaller) and the reservoir of HI locked up in the HVCs is enough to make a Milky Way-sized galaxy.

The velocity dispersion and the velocity centroid of the cloud ensemble can also be used to determine what the most appropriate inertial frame of reference is. A non-inertial frame always gives rise to a larger velocity dispersion than an inertial frame because the former adds a position-dependent velocity in quadrature to each observed radial velocity. A non-zero velocity
Figure 1. HI emission from Complex H integrated over the velocity range 
$-240 \leq V_{\text{LSR}} \leq -170$ km s$^{-1}$, effectively excluding the conventional Galactic gaseous disk. The bright object at $l = 122^\circ$, $b = -21^\circ$ represents the portion of M31 emitting within the chosen velocity range. [from Blitz et al. (1999a)]

centroid suggests that the ensemble is moving relative to the observer. Figure 2 shows the distribution of the velocities of the HVCs in the LSR and GSR frames of reference; the latter are much smaller and suggest that the Galactic Center is a better inertial frame than the Local Standard of Rest. The mean velocity of $-46 \pm 7$ km s$^{-1}$ implies that the Galactic Center is moving with respect to the barycenter of the ensemble. If we concentrate on the clouds with negative velocities seen in the lower panel of Figure 3, the centroid of these clouds is close to the Local Group barycenter ($l = 147^\circ$, $b = -25^\circ$, $v_r = -82$ km s$^{-1}$). Relative to the LSR, the mean velocity of this group of clouds is $-173$ km s$^{-1}$, relative to the GSR, it is $-88$ km s$^{-1}$. However, relative to a frame of reference centered on the barycenter of the Local Group, the LGSR, the mean velocity is only $-28 \pm 10$ km s$^{-1}$. These num-
bers suggest that the barycenter of the Local Group is the proper inertial frame for the HVCs and that the Milky Way is approaching the barycenter at a velocity of about 60–90 km s\(^{-1}\).

**Figure 2.** Left: Histogram of the distribution of HVC velocities relative to the LSR. HVCs which might have a \(V_{\text{LSR}}\) near zero would not be separable from conventional-velocity Galactic emission. Right: Distribution of HVC velocities relative to the GSR. A Gaussian profile was fit to the wings of both histograms: the GSR distribution of the HVCs is more narrowly confined than that relative to the LSR, suggesting that the GSR system is the more appropriate inertial reference frame. The data in both panels are from the Wakker & van Woerden (1991) catalogue of HVCs [from Blitz et al. (1999a)].

Recently, Burton & Braun (this volume) and Braun & Burton (1999) have suggested that there is a separate class of HVCs which they call “Compact HVCs” or CHVCs that are different from those discussed and analyzed above, but somehow share the kinematic properties of the conventional HVCs. In fact, the Burton & Braun clouds are simply a subset of the HVCs compiled by Wakker & van Woerden (1991) with a few additional clouds that fall between the latter’s sampled points. Even though the clouds listed in Burton & Braun are chosen from the smallish end of the Wakker & van Woerden sample, the former have a median surface area \(\lesssim 1.0\) deg\(^2\) compared to 1.5 deg\(^2\) for the Wakker & van Woerden sample (Blitz et al. 1999), and are not more compact than the typical HVCs. Even this difference may result largely because Braun & Burton use the beam deconvolved area and Blitz et al. (1999a) do not. In any event, the small difference hardly warrants a new designation. Apparently, Burton & Braun have succeeded in showing that a representative subset of HVCs has properties of and behaves similarly to the HVC population as a whole.

2.2. DYNAMICAL SIMULATION

The Local Group is dynamically simple, thus it should be possible to simulate the dynamical history of the HVCs and reproduce both the spatial and
kinematic distribution of the clouds. Since 98% of the mass of the Local
Group is in the Milky Way and M31, we modelled the Local Group in Blitz
et al. (1999a) as a modified, restricted 3-body system with the HVCs as
test particles in a potential defined by the Galaxy and M31. The simulation
begins with the HVCs on a regular grid and no initial velocity dispersion.
The Milky Way and M31 are separated initially by 100 kpc and expand
with the Hubble flow; M31 is taken to have twice the mass of the Milky
Way. Enough mass is put into the two galaxies so that they are turned
around from the Hubble flow until they reach their present separation and
velocity of approach. After the start of the simulation, if a particle comes
within 100 co-moving kpc of either galaxy, we assume that the cloud is
accreted. This allows for a somewhat larger interaction radius than the
geometric cross-section of the galaxies to allow for gravitational focusing,
tidal disruption and dynamical friction.

The basic results of the model are insensitive to the exact value of the
relative masses of the two galaxies, or the accretion radius. The model is
exceedingly simple and contains no hydrodynamics (the test particles are
non-interacting), though it is not self-consistent in that all of the mass is
placed in the two galaxies at \( t=0 \) and accretion does not increase the masses
of the galaxies. These shortcomings are compensated by the simplicity of
the model. It contains no free parameters and no fine tuning is done to
improve the comparison with the observations.

The results are shown in Figures 3 and 4. Figure 3 is a comparison of the
simulated and observed spatial distributions of the HVCs with the Mag-
ellanic Stream and the A, C and M complexes removed. The comparison
shows a rather good agreement considering the simplicity of the model. The
model reproduces the two concentrations of clouds, the separation into pos-
itive and negative LSR velocities and the tilt in the positive and negative
velocity cloud groups relative to the Galactic Plane. No extraneous groups
of clouds are produced. No other model considered to date reproduces all
of these features of the HVC spatial distribution. The separation into two
groups occurs naturally in the model because the clouds are distributed
along a wide filament along the line connecting the Milky Way and M31.
The negative LSR velocity clouds are seen along the filament towards the
Local Group barycenter, and the positive LSR velocity clouds are seen pri-
marily in the antibarycenter direction. Both groups are falling toward the
LGSR.

The Magellanic Stream was removed from the comparison because it is
a group of clouds known to be of tidal origin (Mathewson et al. 1974) and is
thus not well represented by our model. Cloud C is by far the largest cloud in
the HVC ensemble and covers more than 1600 deg\(^2\). Clouds A and M, which
are also quite large, have similar velocities and may be related to this large
Figure 3. Comparison of simulated and observed distributions of the HVC ensemble on the sky. Upper: Distribution of all simulated clouds having HI column densities greater than $3 \times 10^{18} \text{ cm}^{-2}$ and $|V_{\text{LSR}}|$ greater than 100 km s$^{-1}$. The size of the symbols is proportional to column density and ranges between $3 \times 10^{18}$ to greater than $3 \times 10^{19}$ cm$^{-2}$. Strictly speaking, these simulated column densities are total ones, i.e. including the dark–matter content. The triangles represent clouds with positive LSR velocities; the pentagons, clouds with negative LSR velocities. This figure represents the distribution of HVCs if the clouds have not been destroyed by passage through a hot intergalactic medium and if collisions between HVCs are rare. Lower: Distribution of observed HVCs but excluding the Magellanic Stream and the Northern Hemisphere complexes A, C, and M, which are evidently relatively nearby and thus not representative of the angular size of individual clouds in the Local–Group ensemble. Positive LSR velocities are denoted by filled contours, negative LSR velocities by open contours. The lower panel was kindly provided by Bart Wakker. [from Blitz et al. (1999a)]

complex. If the A, C and M complex is gravitationally bound, it must be tidally unstable and thus quite nearby. The complex is also very elongated, consistent with tidal shearing. Thus, because of its apparent proximity and tidal shearing, it is also not well represented by our dynamical model and is also excluded from the comparison.
Figure 4. Comparison of the simulated longitude–velocity distribution of the HVCs with the observed situation. Radial velocities are relative to the LSR. Upper: Simulated kinematic distribution of clouds with HI column densities greater than $3 \times 10^{18}$ cm$^{-2}$, plotted separately for $b < 0^\circ$ and for $b > 0^\circ$. Lower: Longitude–velocity diagram of the observed HVC ensemble, as compiled by WvW91. The symbols are proportional in size to the flux from the individual clouds, and are keyed to the individual complexes defined by Wakker (1991). The MC, OA and A,C, and M Complexes are not included in this Figure (see text). Clouds with LSR velocities $|V_{LSR}| < 80$ km s$^{-1}$ are not considered here as HVCs, regardless of their location. [from Blitz et al. (1999a)]
Figure 4 is a comparison of the longitude-velocity plot of the observations and the simulations. Again, the Magellanic Stream and the A, C and M Complex are removed. The simulations reproduce the sinusoidal envelope of the cloud ensemble, the offset toward negative LSR velocities (due to the motion of the Milky Way toward the Local Group barycenter) and the magnitude of the envelope of the distribution. This agreement in the quantitative aspects of the $l - v$ distribution are particularly noteworthy because of the absence of free parameters in the model.

3. Implications and Speculations

If we accept the model at face value, it implies that the HVCs are formed with the earliest structures in the Universe and are the building blocks from which the Milky Way and M31 formed. The HVCs that we see today would then be the leftover building blocks that have not yet been accreted by either galaxy. If the Local Group is not unique, it suggests that structures similar to the HVCs are responsible for all initial galaxy formation, though there would be large differences in how galaxy evolution proceeds depending on the density of the environment (see below).

If the HVCs are almost as old as the Universe, they must be gravitationally bound and tidally stable. If they have typical distances of 1 Mpc as the model suggests, then the observed angular sizes and velocity dispersions imply that to be self-gravitating, about 90% of the matter in the HVCs must be dark; the dark matter may be either baryonic or non-baryonic. Table 1 gives mean derived parameters for the HVCs. For example, the clouds could have a 90% ionization fraction, in which case the emission measure would be $\simeq 10^{-2}$ cm$^{-6}$ pc, an undetectable value at present. If the dark matter is the same as that in the halo of the Milky Way and M31, the ratio of luminous to dark matter is comparable in the HVCs and the galaxies, just what one would expect if the Milky Way and M31 were assembled from HVCs. In this case, the HVCs would also have characteristic masses of $\simeq 10^8$ M$_\odot$, similar to the mini-halos postulated by Ikeuchi (1986) and Rees (1986) to be the first structures to form after recombination.

Our dynamical model allows us to calculate a mass accretion history, which is shown in Figure 5. The present day mass accretion rate is estimated to be 0.8–1.2 M$_\odot$ yr$^{-1}$, approximately what is needed to fuel the present day star formation in the Milky Way (e.g., Blitz 1995). The orbits of some of the HVCs are likely to cross in the region between M31 and the Galaxy, giving rise to collisions between the HVCs. Typical collision velocities can be estimated from Figure 2 to be $\simeq 200$ km s$^{-1}$ possibly giving rise to an x-ray halo surrounding the Milky Way and M31. This gas would probably have a temperature of about 10$^6$ K, and might be detectable. To predict whether
TABLE 1. Mean Derived HVC Properties
[from Blitz et al. (1999a)]

| Quantity              | Value       |
|-----------------------|-------------|
| HI mass               | $1.9 \times 10^7 \, M_\odot$ |
| Total Neutral Gas Mass| $2.7 \times 10^7 \, M_\odot$ |
| Total Mass            | $2.8 \times 10^8 \, M_\odot$ |
| Diameter              | 28 kpc      |
| Distance              | 1 Mpc       |
| $n_{\text{HI}}$       | $0.7 \times 10^{-4} \, \text{cm}^{-3}$ |

or not such an x-ray halo exists, and how large it would be requires adding hydrodynamics to our simulation. The cooling time for the gas would be $> 10^{10} \, \text{yr}$. Collisions between clouds could also be the source of the x-ray halos around poor groups and in denser extragalactic environments.

In our picture, the growth of the Galactic disk is fueled by the gradual accretion of HVCs and is consistent with numerical simulations. Figure 6, for example, shows the results of a hydrodynamical simulation in which a cloud similar to Complex H is being accreted by a disk galaxy similar to the Milky Way. The gas streamer shown in the simulation is similar to that seen in higher contrast versions of Figure 1. Our picture of Milky Way formation is thus more consistent with the episodic accretion model of Searle and Zinn (1968) than it is with the Eggen, Lynden-Bell and Sandage (1962) model. Episodic evolution, furthermore, would lead to metallicity correlations consistent with trends seen in disk stars (Edvardsson et al. 1994).

Finally, the HVCs might be the $z=0$ analogues of the Ly$\alpha$ absorbing systems. If the HVCs are indeed ubiquitous in the Universe, they would correspond in column density to the Lyman limit systems. The frequency distribution of the Ly$\alpha$ absorbers is a power law with a slope of $-1.4$ over 8 orders of magnitude in column density (Wolfe 1993). The slope of the frequency distribution of column densities in the HVCs has the same value of $-1.4$.

4. Predictions and Comparison with other Observations

In our original paper (Blitz et al. 1999a), we made several predictions based on our model.

1. The HVCs should have substantially sub-solar metallicities. These are not expected to be zero, since no extragalactic gas has primordial abundances.
2. The HVCs should have low internal pressures, inconsistent with a Galactic origin. If the clouds are self-gravitating, then the internal pressure within the clouds can be given by

\[ P/k = \frac{3\pi\alpha G\Sigma^2}{20k} \]  

where \( \Sigma \) is the gas surface density, \( \alpha = 2 \) for self-gravitating clouds, and \( k \) is Boltzmann’s constant (Bertoldi & McKee 1992). For self-gravitating HVCs bound by their HI alone and a surface density of \( 3 - 30 \times 10^{18} \text{ cm}^{-2} \), the expected mean hydrostatic pressure within a cloud is expected to be \( 0.016 \) – \( 1.6 \text{ K cm}^{-3} \). If the cloud is in a dark matter potential with 10 times the HI mass, as we expect, the internal
Figure 6. This figure from Kepner (1998) shows the projected hydrogen distribution in a numerical simulation in a disk galaxy by J. Kepner and G. Bryan. In the AMR hydrodynamics simulation of a $\Lambda$-dominated CDM universe, they focused their high resolution mesh on a binary galaxy system with properties similar to the Milky Way. In their simulation, the galactic disks are built up primarily by the gradual accretion of gas clouds with properties similar to those deduced for the HVCs. In this time-slice, the main disk is accreting a gas cloud with properties similar to Complex H. The accreted cloud is being ram-pressure stripped by the hot gaseous halo and is falling towards the disk. Since it has relatively high angular momentum, it eventually settles at the edge of the preexisting disk.

- The pressure would be about 10 times higher, thus pressures of the order of $0.1 - 10 \text{ K cm}^{-3}$ are expected.
- There should be extragalactic analogues of the HVCs in other extragalactic systems.
- There should be H$\alpha$ emission associated with the HVCs at a level at least as great as that detected toward the clouds in the Magellanic Stream if the HVCs are Galactic in origin. If they are extragalactic, the emission measures should be $\lesssim 0.1 \text{ cm}^{-6} \text{ pc}$.

In the past few months, several groups have reported new observations that are consistent with our predictions and appear to contradict the models with a Galactic HVC origin such as the Galactic fountain model:

1. Wakker et al. (1999) recently reported a measurement of sub-solar metallicity on a line of sight toward Mrk 290 in Complex C. They detected SII, a species in the dominant ionization state and which is not depleted onto grains. Wakker et al. obtained values for both the atomic
TABLE 2. Extragalactic HVC Analogues

| Mass       | Diameter | Galaxy | Reference                  |
|------------|----------|--------|----------------------------|
| $1.6 \times 10^8$ | 16       | M101   | van der Hulst & Sancisi (1988) |
| $1.2 \times 10^7$ | 5        | M101   | van der Hulst & Sancisi (1988) |
| $1 \times 10^8$    | 25       | NGC 5668 | Schulman et al. (1996)          |
| $5 \times 10^7$    | 7        | UM422C | Taylor et al. (1995;1996a)     |
| $1.6 \times 10^8$  | 16 (?)   | UM 456B| Taylor et al. (1995;1996a)     |
| $1.4 \times 10^8$  | 8 (?)    | F495-IVB| Taylor et al. (1996b)           |
| $7.9 \times 10^7$  | 38       | NGC 628| Kamphuis & Briggs (1992)        |
| $9.5 \times 10^7$  | 47       | NGC 628| Kamphuis & Briggs (1992)        |
| $2.1 \times 10^8$  | 6        | NGC 3227| Mundell et al. (1995)           |
| $2 \times 10^7$    | 28       | Local Group | This paper; Table 1        |

and ionized gas components and concluded that the abundance along this line of sight is only 0.094 solar. They concluded that this cloud represents an accretion event of an extragalactic cloud, in agreement with our predictions. Complex C has by far the largest angular size of any HVC, and is probably the nearest. If this cloud is of extragalactic origin, it suggests that the other smaller clouds are also extragalactic.

2. Sembach et al. (1999) observed the ionized edges of HVCs in the direction of Mrk 509 and PKS 2155-304 and detected strong C IV absorption, with little or no CII or SiII. The authors concluded that the clouds are low density ($n_H \simeq 10^{-4} \text{ cm}^{-3}$), large (greater than several kiloparsecs) clouds with $P/k \simeq 2 \text{ K cm}^{-3}$. This pressure is just in the range expected for self-gravitating, dark matter confined HVCs, is four orders of magnitude less than the pressure in the midplane of the Milky Way and two orders of magnitude less than expected in the Galactic halo (Wolfire et al 1995). The density is also in good agreement with the derived value given in Table 1.

3. Extragalactic analogues of the HVCs have been seen toward a number of galaxies. A list of such clouds is given in Table 2. These clouds were found serendipitously in the course of mapping other objects. Many are seen in projection against other galaxies, some are seen as distinct objects separated in both position and velocity from the parent galaxy. Such clouds would appear as HVCs if viewed from the target galaxy. Clearly numerous extragalactic HI clouds have been found with properties similar to those of the HVCs given in Table 1.

Several blind surveys of HI have been undertaken, notably by Zwaan et al. (1996), and more recently by Spitzak & Schneider (1999). In the
Zwaan et al. survey, no extragalactic analogues were found without optical counterparts. Spitzak & Schneider found one cloud without an optical counterpart. Neither survey is particularly sensitive to HI masses typical of what we expect from extragalactic HVCs, though a few probably should have been detected in the Zwaan et al. survey if it is as sensitive as was claimed. It is difficult to predict how many HVC analogues should be detected since the number associated with a galaxy group or cluster probably depends sensitively on the density of the environment. It is therefore difficult to assess whether the non-detections in the blind searches (except for Spitzak & Schneider) are significant. A targeted, high sensitivity survey in the direction of a good Local Group analogue might well decide this issue.

4. Hα has been detected toward Clouds A, C and M (Tufte et al. 1998) as well as toward the Magellanic Stream (Weiner & Williams 1996). There is some question of whether the emission toward the Magellanic Stream is due to photoionization from the Galactic ionizing radiation that leaks out of the plane of the Milky Way, or is due to shock heating from the clouds as they pass through the diffuse gas in the Galactic Halo. However, regardless of what produces the Hα, HVCs that are of Local Group origin should have lower emission measures than those detected toward either cloud complex. The Hα measurements are a critical test of the Local Group model and observations toward the very high velocity clouds ($|v_r| > 200$ km s$^{-1}$) should give emission measures no higher than $\sim 0.1$ cm$^{-6}$ pc. Measurements are currently underway by the Wisconsin group using their WHAM instrument, by a Maryland–Carnegie group and by a group in Australia. If the HVCs are Galactic (distances $< 50$ kpc), their Hα surface brightnesses should be at least as large as those already detected. Results should be available within the next year.

The low metallicity, pressure and density detected along several lines of sight support a Local Group origin. The detection of extragalactic HI clouds with properties similar to those inferred if the HVCs are Local Group objects suggests that such clouds do exist in intergalactic regions. The relative paucity of HVC analogues seen in blind HI surveys may simply be a result of insufficient sensitivity or sky coverage, and more sensitive observations perhaps directed toward poor galaxy groups might usefully be undertaken. Hα measurements will provide a critical test which should be able to distinguish between Galactic or extragalactic locations for the HVCs.
5. Other Possible Origins

One possibility other than a Local Group origin for the HVCs is that the clouds are extensive tidal debris from either previous passages of the Magellanic clouds or other nearby dwarfs. Bland-Hawthorne et al. (1998) have recently suggested that the so-called “Smith Clouds” are related to tidal streaming associated with the passage of the Sgr dwarf (Ibata, Gilmore & Irwin 1994). However, an important constraint on tidal models is the crossing time for HVCs which can be written as follows:

\[ t_c = 17.1 \frac{\Omega^{1/2} r_{\text{kpc}}}{\Delta v} \text{ Myr}, \]  

where \( r_{\text{kpc}} \) is the distance from the Galactic Center in kpc and \( \Delta v \) is the FWHM of the HI line averaged over the cloud. The mean value of \( \Delta v \) for the HVCs is 30 km s\(^{-1}\), and the median value of \( \Omega \) is 1.5 deg\(^2\) (Blitz et al. 1999). Thus the crossing time for a typical HVC is about 1 Myr/kpc, or about 50 Myr at the distance of the Magellanic clouds. HVCs at that distance cannot be gravitationally bound (except perhaps for Complex C, H and the Anticenter Complex). Clouds at 50 kpc therefore double in size in a crossing time which corresponds to a decrease in density of an order of magnitude. Thus HVCs from a tidal origin should not be able to survive for more than 1 – 2 crossing times. The orbital time for the Magellanic clouds is about 200 Myr, far too long for HVCs to have been the result of a prior passage. The Magellanic stream itself has a much larger \( \Omega \) than the typical HVC and thus has a longer crossing time. Nevertheless, the Magellanic Stream is identified over only about 1/4 of the sky, suggesting that even those HI clouds are destroyed in about 50 Myr. No other dwarf companions are close enough to the Milky Way to have produced the extensive tidal debris that would be necessary to explain the HVCs.

The Galactic fountain model postulates that the HVCs are HI clouds which have condensed from gas expelled into the halo by supernovae and stellar winds (Shapiro & Field 1976; Bregman 1980). It has long been known that the Galactic fountain model cannot produce HI clouds with radial velocities in excess of the circular speed of the Galaxy of about 220 km s\(^{-1}\). Many HVCs have significantly larger velocities. Furthermore, the recent evidence for low HVC pressures and densities, the low metallicities, and the inability of the fountain models to reproduce the observed features seen in Figures 3 and 4 make the Galactic fountain untenable for the majority of HVCs. Nevertheless, even the Local Group model seems to produce insufficient numbers of clouds at low LSR velocities (clouds near \( V_{\text{lsr}} = 100 \text{ km s}^{-1} \) – see Figure 4). Some of these clouds are not fully separated in velocity from the main Galactic emission and may therefore yet be part of the normal Galactic emission or a Galactic fountain phenomenon. Just
as $H\alpha$ measurements become a good test of the Local Group origin for the HVCs, it may be that the lower velocity HVCs will be relatively bright $H\alpha$ emitters.

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