Constraints on the Space Density of Extragalactic HVCs

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Abstract. High Velocity Clouds (HVCs) have recently attracted renewed attention as being long lived, massive dark matter dominated clouds of primordial composition distributed throughout the Local Group. In this picture the HVCs would contain a few $10^7 M_\odot$ of H I and would be at distances of a few hundred kpc to 1.5 Mpc from the Local Group barycenter. If this extragalactic interpretation of HVCs is true, similar clouds are expected in other galaxy groups and around galaxies. We discuss the limits blind H I surveys and QSO absorption line studies put on this proposed population of clouds.

1. Introduction

The nature of high velocity clouds (HVCs) still remains a mystery. Several explanations of their origin have been set forth by Wakker & van Woerden (1997) in their review of forty years of HVC research. They conclude that no single origin can explain all observed HVCs and subdivide all known HVCs into different classes. Well established is the explanation for the Magellanic Stream, the largest H I structure observed in the sky, except for the gaseous disk of the Milky Way itself. This HVC is likely the result of tidal interaction between the Milky Way and the Magellanic Clouds, where LMC gas is stripped away and spread along an orbit around the Milky Way. However, this HVC is not typical for the large number of clouds presented by Wakker & van Woerden (1991), the standard catalog of HVCs. Most clouds require alternative explanations.

The main uncertainty in understanding the nature of the HVCs is that their distances are difficult to determine. The absence of starlight in HVCs prevents the use of spectroscopic parallax methods commonly-used to determine distances to stars in the nearest galaxies. Some distance brackets have been specified with the absorption line method where spectra of stars with known distances are checked for the presence of (e.g.) Ca, Fe, and Mg absorption features (Van Woerden et al. 1999). Recently, Balmer recombination line emission driven by reprocessing of the UV ionizing radiation originating from hot, young stars in the Galactic disk has been used to specify distances to a few clouds (Bland-Hawthorn et al. 1998, Bland-Hawthorn & Maloney 1999). These measurements require an accurate model for the Galactic ionizing field, and work best for clouds with large perpendicular distances from the Galactic disk. Braun & Burton (1999) present yet another distance estimator. For a cool HVC core they use the measured H I column density and the angular size to calculate an H I volume density which
depends on the distance to the cloud. Assumptions about the thermodynamics of the H I gas yields a likely density and hence a distance.

Oort (1966) was the first to consider HVCs in an extragalactic context. His distance estimation assumed that the clouds are self-gravitating, stable entities. By comparing their solid angle on the sky, brightness temperature, and velocity dispersion Hulsbosch (1975) found that the typical distance would be approximately 10 Mpc, which places the clouds outside the Local Group (LG) and implies that their neutral hydrogen mass would be \( \sim 10^9 M_\odot \), comparable to that of normal spiral galaxies. At these distances, the clouds should be participating in the Hubble expansion, rather than approaching the Milky Way.

Blitz et al. (1999) and Braun & Burton (1999) have recently revived the idea that HVCs are extragalactic. These authors show that the clouds' distribution on the sky, as well as their kinematics as an ensemble are consistent with a model in which HVCs are distributed throughout the LG, at typical distances of a few hundred kpc (Braun & Burton) to 1 Mpc (Blitz et al.). In order to make the total mass of the HVCs consistent with the assumption of self-gravity, the authors suggest that, like galaxies, HVCs are dominated by dark matter. This dark matter provides the binding potential that keeps the clouds from falling apart; the only directly observable constituent, H I, is only 10% of the total mass. In this scenario, the HVCs are either remnants from the formation of the LG or representatives from an intergalactic population of dark matter dominated mini-halos in which hydrogen has collected and remained stable on cosmological time scales.

A theoretical basis for the LG explanation is provided by hierarchical clustering scenarios that explain the formation of galaxies by many generations of mergers of smaller masses. Large numbers of proto-galactic gas clouds might survive to the present day if the mergers are not fully efficient. However, only about ten percent of the predicted number of halos have been identified as dwarf galaxies (Klypin et al. 1999, Moore et al. 1999). The association of HVCs with this missing population makes an appealing picture for the LG explanation.

Clearly, if the HVC phenomenon is a common feature of galaxy formation and evolution, then extragalactic surveys of the halos and group environments of nearby galaxies should show evidence for this population. Also the incidence of QSO absorption line systems should be in agreement with this idea.

## 2. The H I Mass Function of HVCs in the Local Group

Determining the space density of gas-rich galaxies and possible intergalactic gas clouds as a function of H I mass has been, and continues to be, one of the main objectives of extragalactic 21cm surveys. At this meeting the results from several H I surveys with varying sensitivity and survey volume have been presented, and it is clear that at this moment there is still no consensus on the shape and normalization of the H I mass function (HI MF, see contributions by Henning, Schneider, Staveley-Smith, Verheijen, Webster). Especially at low H I masses (\( M_{\text{HI}} < 10^{7.5} h^{-2}_{65} M_\odot \)), there is considerable uncertainty due to the small number of detections. Schneider, Spitzak & Rosenberg (1998) have found evidence for a steep upturn in the tail of the HI MF. Although this steep tail has a tantalizing similarity to the signature of massive HVCs, it appears that
at least one of the two H i signals responsible for the rise comes from a normal galaxy, and the other is too close to a bright star to exclude faint optical emission (Spitzak & Schneider 1999).

In order to develop a reference frame for the number density of HVCs in the LG, we determine the LG H i MF from H i measurements of all known members as compiled by Mateo (1998). The top panel of Figure 1 shows the resulting Hi MF, constructed from 22 LG galaxies in which H i has been detected. Also incorporated in this mass function are the recent H i detections in dwarf spheroidals (Blitz & Robishaw 2000). A simple correction for incompleteness due to obscuration by dust in the Zone of Avoidance has been made (see Zwaan & Briggs 2000). Also shown is the field Hi MF determined by Zwaan et al. (1997), scaled vertically so as to fit the points around the knee in the Hi MF where the curve has been measured accurately. Note that the Hi MF of optically selected galaxies in the LG is remarkably flat, with \( \alpha \approx -1.0 \). Dwarf galaxies with \( M_{\text{HI}} < 10^{8} M_\odot \) contribute only \( \sim 2.5\% \) to the total H i budget of the LG.

The second panel of Figure 1 shows the same curve, but overlaid is now the Hi MF of HVCs if they were self-gravitating clouds distributed throughout the LG, as proposed by Blitz et al. (1999). We use the HVC parameters from the compilation of HVCs of Wakker & van Woerden (1991). For each cloud, the distance at which it is gravitationally stable is calculated, assuming that the ratio of baryonic to total mass is \( f \). We choose to let \( f \) vary from 0.0125 to 0.2 and calculate the mass functions. The virial distance of a cloud scales in direct proportion to \( f \), and hence the mass with \( f^2 \). It is obvious from Figure 1 that high values of \( f \) are in variance with the observed field Hi MF: 21cm surveys should have detected in the order of 10 dark H i clouds for every normal galaxy with the same H i mass in the range \( 10^{7.5} \) to \( 10^{9} M_\odot \). None of the H i surveys to date has found evidence for such a large population of H i clouds without optical identification.

The space density of HVCs in the LG can only be brought into agreement with the observed field Hi MF if the median value of \( f \) is lowered to \( \sim 0.02 \), a value much lower than what is normally observed in galaxies. The median distance of such clouds must be smaller than \( \sim 200 \) kpc. At these distances the clouds do not fit logically in a model in which they are distributed throughout the LG.

### 3. Expected HVC Detections in 21cm Surveys

More specific estimates of the expected number of extragalactic HVC detections can be made by simulating the cloud populations around known galaxies and groups. A number of 21cm surveys exist that are capable of sensing the presence of the extragalactic HVC population in the outskirts of external groups and galaxies.

For instance, the Arecibo H i Strip Survey (AHiSS, Sorar 1994, Zwaan et al. 1997), an unbiased drift-scan survey at two constant declination strips, is very suitable for assessing the HVC problem. Zwaan & Briggs (2000) use various redshift surveys and catalogs of galaxy groups to calculate that the strips probe the halos of some 300 galaxies and 14 groups with impact parameters of \( \leq 1 \) Mpc. The volumes around the galaxies and groups are filled with synthetic
Figure 1. Top panel: H I mass function of the Local Group (LG).
The points show the space density of LG members containing H I, after
correcting for incompleteness. The solid line shows the field H I MF
from Zwaan et al. (1997), scaled vertically so as to fit the points. The
dotted line is a H I MF with a steep upturn at the low mass end, recently
proposed by Schneider et al. (1998) Second panel: H I mass functions
for extragalactic HVCs. The histograms shows the space density of
Blitz et al. HVCs if they are put at the critical radii for gravitational
stability assuming different values of f (from right to left: f=0.2, 0.1,
0.05, 0.025, 0.0125). The HVC H I MF is consistent with the field H I MF
if f ≤ 0.02 and the median distance ≤ 200 kpc.

populations of HVCs, with properties similar to what is proposed by Blitz et al.
(1999). The group halos are filled with 450 clouds, approximately the number of
HVCs listed by Wakker & van Woerden (1991), excluding the large complexes
which are excluded from the Blitz et al. analysis. To calculate the number
of clouds around galaxies, the number of clouds associated with each galaxy is
scaled in direct proportion to the ratio of the galaxy luminosity compared to the
integral LG luminosity.

The number of expected detections was calculated taking into account the
column density, size, and velocity width of the HVC population as measured
by Wakker & van Woerden (1991). Several radial distribution functions for the
clouds have been tested, but this does not seem to have a strong influence on
the expected number of detections: ∼ 70 HVC detections in groups and ∼ 250
detection around galaxies should have been made. Note that the group member
galaxies have not been removed from the list of galaxies, so these numbers should
not be simply added to predict a total number of detections. The analysis is sensitive to clouds with H I masses \(> 10^7 \, M_\odot\), not only to the most massive ones.

These predictions are in sharp contrast with the results of the AHfSS analysis: all H I detections away from the Zone of Avoidance could be optically identified with galaxies containing stars. Other surveys have turned up a few instances of dark H I clouds, but these are all found to be confined to the gravitational potential of a bright optical galaxy, and are much too scanty to agree with the numbers calculated above. Kilborn et al. (2000) report on the first discovery of an isolated extragalactic H I cloud without optical identification, but this cloud too might be explained as a very high velocity cloud in the outskirts of the Milky Way-LMC system.

4. QSO Absorption Line Statistics

A completely independent way of investigating the idea of extragalactic HVCs is provided by QSO absorption line statistics. Charlton, Churchill & Rigby (2000) showed that the incidence of Mg II and Lyman limit absorption systems is in conflict with the idea that extragalactic groups contain several hundreds of clouds with typical H I masses of \(10^7 \, M_\odot\). We illustrate this same point here by plotting the column density distribution function of H I \(f(N_{HI})\) for the proposed HVC population. This function describes the chance of finding an absorber of a certain H I column density along a random line of sight per unit distance.

For the HVCs, we again use the Wakker & van Woerden catalog. The area covered by each cloud is calculated from its measured solid angle \(\Omega\) on the sky, and its distance based on the assumption of virial equilibrium. An area function \(\Sigma(N_{HI})\) that describes the total area in Mpc\(^2\) that is covered by the ensemble of clouds as a function of \(N_{HI}\) is calculated by binning the clouds in column density, and adding the areas. The column density distribution function can be calculated from

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f(N_{HI}) = \frac{c}{H_0} \frac{\phi^* \Sigma(N_{HI})}{dN_{HI}},
\]

where \(\phi^*\) is the space density of groups. Charlton et al. (2000) derive \(\phi^*\) from the CfA redshift survey by dividing the number of identified groups by the total survey volume and find \(\phi^* = 3 \times 10^{-4}\). This is a conservative estimate since it does not incorporate a correction for incompleteness of the survey at higher redshifts. Ramella et al. (1999) compose a catalog of groups from the ESO Slice Project (ESP) redshift survey. Within the volume of \(1.9 \times 10^5 h_{100}^3\) Mpc\(^3\) at the effective depth of \(z = 0.16\) they identify 231 groups with at least three members. The space density of groups within that volume is therefore at least \(1.2 \times 10^{-3} h_{100}^3\) Mpc\(^{-3}\). If we limit the calculation to the volume at the sensitivity peak of the survey at \(z = 0.1\) the value of \(\phi^*\) rises to \(2.0 \times 10^{-3} h_{100}^3\) Mpc\(^{-3}\), which illustrates the effect of incompleteness. As a conservative estimate we adopt \(\phi^* = 1.2 \times 10^{-3}\) Mpc\(^{-3}\) for the calculation of \(f(N_{HI})\). The resulting \(f(N_{HI})\) is shown in Figure 2 as a dashed histogram.

The same calculation can be performed for individual galaxies. In this case we have to integrate over the luminosity function of galaxies, and the num-
ber of clouds associated with each galaxy is again scaled with the galaxy luminosity compared to the integral luminosity of the LG. For the luminosity function we adopt the average values from different large galaxy redshift surveys (see Fukugita, Hogan & Peebles 1998): $M_B^* = 19.5$ mag, $\alpha = -1.1$ and $\phi^* = 0.020$ Mpc$^{-3}$. The resulting $f(N_{HI})$ is shown as the solid histogram in Figure 2.

For comparison, the measured values of $f(N_{HI})$ are shown as points with errorbars. The leftmost points represent the high $N_{HI}$ part of the Lyman $\alpha$ forest measured by Hu et al. (1995). The HVCs cover the Lyman limit regime, the point here is taken from Petitjean et al. (1991). The forest and Lyman limit points are all derived from high $z$ ($>2$) data, a low $z$ $f(N_{HI})$ is not available in this regime. The points for damped Lyman $\alpha$ systems at the highest $N_{HI}$ part are taken from Rao & Turnshek (2000) and are for $z \approx 0.8$. The straight line is the canonical fit to $f(N_{HI})$ at $z = 0$ with a slope $-1.5$. As was noted by Blitz et al. (1999), the shape of $f(N_{HI})$ for HVCs agrees well with the general observed trend. However, this plot clearly illustrates that the simulated $f(N_{HI})$ for clouds exceeds the measured one by a large factor.

This points can be made more qualitatively by calculating $dN/dz$, the number of absorbers per unit redshift, by integrating over $f(N_{HI})$. For the groups we derive $dN/dz = 6$ and for clouds around individual galaxies we find $dN/dz = 27$. Extrapolating the results of Stengler-Larrea et al. (1995) on Lyman limit systems to $z = 0$ yields $dN/dz = 0.25 \pm 0.15$. The conclusions that we can draw from this exercise are similar to those of Charlton et al.: QSO absorption line statistics are inconsistent with the hypothesis that galaxies and galaxy groups are surrounded by a large population of $M_{HI} = 10^7 M_\odot$ gas clouds.

5. Discussion

The hypothesis that most HVCs are primordial gas clouds with typical $H_\text{i}$ masses of a few $\times 10^7 M_\odot$ at distances of $\sim 1$ Mpc from the Galaxy is not in agreement with observations of nearby galaxies and groups and with QSO absorption line statistics. Blind $H_\text{i}$ surveys of the extragalactic sky would have detected these clouds if they exist around all galaxies or galaxy groups in numbers equal to those suggested for the Local Group. These results are highly significant: the Arecibo $H_\text{i}$ strip survey would have detected approximately 250 clouds around individual galaxies and 70 in galaxy groups. Furthermore, the measured incidence of QSO absorption line systems $dN/dz$ is at least a factor 20 lower than what would be expected if all groups and galaxies were surrounded by a collection of $H_\text{i}$ clouds similar to what is proposed for the Local Group.

Several additional observations could help identifying the true nature of HVCs. Measuring the $H\alpha$ flux in HVCs can yield accurate distances, provided that the UV ionizing field around the Milky Way is accurately known (Bland-Hawthorn et al. 1998, Bland-Hawthorn & Maloney 1999). Also, determining metal abundances in HVCs is a useful method to distinguish between different HVC scenarios. If the clouds are primordial remnants of the formation of the Local Group they would not have been contaminated with these heavier elements and would retain a composition closer to the pristine environment of the early Universe.
Figure 2. The simulated column density distribution function \( f(N_{\text{HI}}) \) for HVCs  
\( a) \) if they were at typical distances of 1 Mpc distributed throughout all galaxy groups (dashed histogram);  
\( b) \) if they existed around all galaxies in the local Universe (solid histogram). The points are measured values of \( f(N_{\text{HI}}) \) from QSO absorption line studies.

Results to date have been confusing, since different teams report different measured metallicities, even in the same cloud. HST spectra of Complex C taken in the direction of background source Mrk 290 yield a sulphur abundance ten times lower than that of the gas layer of the Milky Way (Wakker et al. 2000). On the other hand, very recent data from FUSE, probing a different position in the same cloud, show an abundance of iron approximately half that found in the solar neighborhood (Murphy et al. 2000). Furthermore, Sembach et al. (2000) report on FUSE observations that show the first detection in a HVC of O vi, a high ionization level probably produced in interactions between the HVC and the halo gas of the Galaxy.

The conclusion that can be drawn at this moment is that HVCs are probably a mixture of several species with different origin. Some are clearly the result of gravitational interactions, some might be produced in a Galactic fountain where hot gas is blown out of the Galactic disk, into the halo, where it cools and precipitates on the Galaxy. Some might be primordial gas clouds distributed throughout the Local Group. Braun & Burton (1999, 2000) limit their calculations to a subsample of some 80 compact HVCs, and place them at a median distance of 650 kpc at which the H i mass would be \( \sim 10^7 M_\odot \). For such a population, the limits from both QSO absorption line results and 21cm surveys are much weaker. Future deep 21cm surveys that reach minimal detectable H i masses of \( 10^6 M_\odot \) in nearby groups will provide the definitive answer.
References

Bland-Hawthorn, J., & Maloney, P. R. 1999, ApJ, 510, L33
Bland-Hawthorn, J., Veilleux, S., Cecil, G. N., Putman, M. E., Gibson, B. K., & Maloney, P. R. 1998, MNRAS, 299, 611
Blitz, L., Spergel, D. N., Teuben, P. J., Hartmann, D., & Burton, W. B. 1999, ApJ, 514, 818
Blitz, L. & Robishaw, T. 2000, astro-ph/0001142
Braun, R., & Burton, W. B. 1999, A&A, 341, 437
Braun, R., & Burton, W. B. 2000, astro-ph/0004033
Charlton, J. C., Churchill, C. W., & Rigby, J. R. 2000, astro-ph/0002001
Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1998, ApJ, 503, 518
Garcia, A. M. 1993, A&AS, 100, 47
Hu, E. M., Kim, T., Cowie, L. L., Songaila, A. & Rauch, M. 1995, AJ, 110, 1526
Hulsbosch, A. N. M. 1975, A&A, 40, 1
Kilborn, V. et al. 2000, astro-ph/0005267
Klypin, A. A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, L9
Mateo, M. L. 1998, ARA&A, 36, 435
Moore, B., Ghigna, F., Governato, F., Lake, G., Stadel J., Tozzi, P. 1999, ApJ, 524, L19
Murphy, E. et al. 2000, astro-ph/0005408
Oort, J. H., Bull. Astr. Inst. Neth. 1966, 18, 421
Petitjean, P., Webb, J. K., Rauch, M., Carswell, R. F. & Lanzetta, K. 1993, MNRAS, 262, 499
Putman, M. E. et al. 1998, Nature, 394, 752
Rao, S. M., Turnshek, D. A. 2000, astro-ph/9909164
Ramella, M. et al. 1999, A&A, 342, 1
Schneider, S. E., Spitzak, J. G., Rosenberg, J. L. 1998, ApJ, 507, L9
Sembach, K. R. et al. 2000, astro-ph/0005012
Sorar, E. 1994, Ph.D. Thesis, University of Pittsburgh
Spitzak, J. G., & Schneider, S. S. 1999, ApJS, 119, 159
Stengler-Larrea, E. A., et al. 1995, ApJ, 444, 64
Wakker, B. P., & van Woerden, H. 1991, A&A, 250, 509
Wakker, B. P., & van Woerden, H. 1997, ARA&A, 35, 217
Wakker, B. P. et al. 1999, Nature, 402, 388
van Woerden, H., Schwarz, U. J., Peletier, R. F., Wakker, B. P., & Kalberla, P. M. W. 1999, Nature, 400, L138
Zwaan, M. A., Briggs, F. H., Sprayberry, D., & Sorar, E. 1997, ApJ, 490, 173
Zwaan, M. A., & Briggs, F. H. 2000, ApJ, 530, L61