THE SPACE DENSITY OF PRIMORDIAL GAS CLOUDS NEAR GALAXIES AND GROUPS
AND THEIR RELATION TO GALACTIC HIGH-VELOCITY CLOUDS

MARTIN A. ZWAAN AND FRANK H. BRIGGS
Kapteyn Astronomical Institute, Postbus 800, 9700 AV Groningen, Netherlands; zwaan@astro.rug.nl, fbriggs@astro.rug.nl

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ABSTRACT

The Arecibo H i Strip Survey probed the halos of ~300 cataloged galaxies and the environments of ~14 groups with sensitivity to neutral hydrogen masses \( \gtrsim 10^7 M_\odot \). The survey detected no objects with properties resembling the high-velocity clouds (HVCs) associated with the Milky Way or Local Group. If the HVCs were typically \( M_{HI} = 10^{15} M_\odot \) objects distributed throughout groups and galaxy halos at distances of ~1 Mpc, the survey should have made ~70 HVC detections in groups and ~250 detections around galaxies. The null detection implies that HVCs are deployed at typical distances of ~200 kpc from the galaxies or group barycenters. If the clouds are in virial equilibrium, their average dark matter fraction must be 98% or higher.

Subject headings: galaxies: ISM — galaxies: luminosity function, mass function — intergalactic medium — Local Group — radio lines: ISM

1. INTRODUCTION

After an extensive review of the high-velocity cloud (HVC) literature, Wakker & van Woerden (1997) concluded that no single origin can account for the properties of the HVC population of neutral hydrogen clouds that surround the Milky Way. Instead, several mechanisms, including infalling extragalactic clouds, cloud circulation within the Galactic halo driven by a galactic fountain, and a warped outer arm extension to the Galaxy, must be invoked. The Magellanic Stream and associated HVC complexes require an explanation that relies on tidal interactions within the Local Group (LG; see Putman et al. 1998).

A defining property for the HVCs has been the lack of associated stellar emission. This also means that spectroscopic parallax methods cannot be used to measure distances to the clouds, and the lack of known distances, in turn, hinders the calculation of the clouds’ physical properties. Recently, absorption lines (see van Woerden et al. 1999) and Balmer recombination line emission driven by reprocessing of the ionizing radiation originating in the Galactic star-forming regions (Bland-Hawthorn et al. 1998; Bland-Hawthorn & Maloney 1999) have been used to specify distances to a few of the clouds, indicating a range of distances from within the Galactic halo to greater than 50 kpc.

Recent interest has returned to the idea that HVCs could be primordial objects raining on the Galaxy, as either remnants of the formation of the LG or as representatives from an intergalactic population of dark matter–dominated minihalos in which hydrogen has collected and remained stable on cosmological timescales (Blitz et al. 1999, hereafter BSTHB; Braun & Burton 1999, hereafter BB). The requirement of gravitational stability without star formation places lower limits on the distances of the clouds from the Sun—a sort of independent distance indicator that can be applied to each cloud individually, depending on its H i flux, angular extent, and velocity-profile width. Typical derived distances are of order 1 Mpc, implying that this segment of the HVC population (1) inhabits the LG rather than the Galactic halo, (2) has typical H i mass per cloud greater than ~\( 10^7 M_\odot \), and (3) increases the LG H i mass budget by contributing ~4 \( \times 10^{10} M_\odot \) in the case of the BSTHB sample. For the BB sample, which is restricted to 65 confirmed “compact HVCs,” the integral H i content adds ~\( 10^9 M_\odot \) to the LG.

Further impetus to search for a primordial population of low-mass objects comes from simulations of galaxy and group formation (see Klypin et al. 1999), which predict of order 10 times more ~\( 10^5 M_\odot \) minihalos in the LG than can be counted in the dwarf galaxy population. The association of HVCs with this missing population, as well as arguments based on the kinematics of the cloud population (BSTHB and BB), makes an appealing picture for the extragalactic/LG explanation.

Similar concerns motivated the extragalactic 21 cm line survey by Weinberg et al. (1991), whose study of several representative environments (clusters and voids) found only gas-rich galaxies containing stars. Several extragalactic H i surveys of substantially larger volumes and more sensitive H i mass limits have also found no objects with HVC properties (i.e., H i detections without associated starlight; Zwaan et al. 1997; Spitzenz & Schneider 1998; Kilborn, Webster, & Staveley-Smith 1999).

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. We take two approaches to the problem of placing the local HVC population in an extragalactic context. The first (in §§ 3 and 4) is to compute the H i mass function for the LG, both for optically selected group members and for group members plus HVC populations as modeled by BSTHB and BB. A second, separate approach (§ 4) is to calculate the probability that the narrow strip that the Arecibo 1 H i Strip Survey (AHSS; Sorar 1994; Zwaan et al. 1997) makes through the halos of ~200 galaxy halos and ~14 groups would detect members of HVC populations in those systems.

2. THE LOCAL GROUP H i MASS FUNCTION

The H i mass function (HiMFF) is used in extragalactic astronomy to quantify the space density of gas-rich galaxies and possible intergalactic clouds as a function of H i mass. For the

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field galaxy population, the HiMF has been determined accurately for \( M_{\text{HI},i} > 10^{-5} h_{65}^{-2} M_\odot \) and can be fitted satisfactorily with a faint-end slope of \( \alpha \approx -1.2 \) (Briggs & Rao 1993; Zwaan et al. 1997; Kilborn et al. 1999). At lower \( M_{\text{HI},i} < 10^{-5} h_{65}^{-2} M_\odot \), where 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 HiMF. Although this steep tail has a tantalizing similarity to the signature of massive HVCs, it appears that at least one of the two \( \text{HI} \) 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 1998).

We construct the HiMF for the LG from \( \text{HI} \) measurements of all known LG members as compiled recently by Mateo (1998). Within the LG volume, a total of 22 galaxies are known in which \( \text{HI} \) has been detected. The statistics are therefore poor, and consequently the HiMF is noisy. The LG HiMF is in one sense the best measured HiMF, with data over 6 orders of magnitude compared with the 3 or 4 orders of magnitude for the determination of the field galaxy population. On the other hand, the LG HiMF may suffer from severe selection effects because of obscuration by dust in the disk of the Milky Way. In order to estimate how many galaxies might have escaped detection so far, Mateo (1998) plotted the cumulative number of galaxies as a function of \( 1 - \sin |b| \), for the total sample of LG galaxies. If LG galaxies were distributed equally over the sky, the resulting histogram should be a straight line. We applied the same method to the sample of galaxies with \( \text{HI} \) detections and found that four to seven galaxies with \( \text{HI} \) masses greater than \( 10^4 M_\odot \) are likely to be missing at low Galactic latitude. The missing galaxies would be predominantly the ones with low optical surface brightness, but since there is no clear correlation between surface brightness and \( \text{HI} \) mass, it is not possible to make a more refined correction to the HiMF than just adding one galaxy to each half-decade mass bin below \( M_{\text{HI},i} = 10^4 M_\odot \). For larger galaxies with \( M_{\text{HI},i} > 10^4 M_\odot \), we assume that the census of the LG galaxy population is complete (see Henning et al. 1998).

The result is presented in the top panel of Figure 1, where the points represent the LG HiMF and the line is the field HiMF derived by Zwaan et al. (1997) and scaled vertically so as to fit the points in the region around \( M_{\text{HI},i} = 10^4 M_\odot \). The curve has been measured accurately. This scaling is justified given the fact that the HiMF for optically selected and \( \text{HI} \)-selected galaxies is identical (see Briggs & Rao 1993; Zwaan et al. 1997). The scaling accounts for the overdensity of the LG, which amounts to a factor of 25, assuming that the LG volume is 15 Mpc\(^3\). Also shown is an HiMF with a steep upturn proposed by Schneider et al. (1998). The large divergence between the extrapolated curves from Zwaan et al. (1997) and Schneider et al. (1998) illustrates the uncertainty in HiMF below \( M_{\text{HI},i} = 10^4 M_\odot \). The LG HiMF for optically selected galaxies is remarkably flat, with the faint-end slope of a Schechter function fit of \( \alpha \approx 1.0 \).

Studies of the \( \text{HI} \) content of galaxies in different environments (including voids [Szhoumorou et al. 1996], clusters [McMahon 1993], and groups [Kraan-Korteweg et al. 1999]) have shown that the shape of the HiMF for \( M_{\text{HI},i} > 10^4 M_\odot \) is independent of cosmic density. The fact that we find here that the HiMF of optically selected LG members is flat down to \( \text{HI} \) masses of a few times \( 10^4 M_\odot \) does not, however, ensure that the field HiMF is also flat to these low masses. Although the crossing time of the LG is approximately equal to a Hubble time, there are clear indications of interactions (Mateo 1998 and references therein). The \( \text{HI} \) distributions in the lowest luminosity LG dwarfs are often highly asymmetric, perhaps indicative of tidal distortions. It is quite possible that low-mass systems are destroyed or merged, which could cause the LG HiMF to be flatter than that of the field.

### 3. \( \text{HI} \) Mass Functions for Extragalactic HVCs

We now derive HiMFs for the population of extragalactic HVCs as proposed by BSTHB and BB. For the compact, isolated HVCs identified by BB, we estimate \( \text{HI} \) masses by using their measurements of the integrated fluxes and the assumption that all clouds are at the same 1 Mpc distance, suggested by

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![Figure 1](image_url)

**Fig. 1.**—*Top panel:* HiMF of the LG. The points show the space density of LG members containing \( \text{HI} \), after correcting for incompleteness. The solid line shows the field HiMF from Zwaan et al. (1997), scaled vertically so as to fit the points. The dotted line is an HiMF with a steep upturn at the low-mass end, recently proposed by Schneider et al. (1998). *Second panel:* HiMFs for extragalactic HVCs. The dark-gray histogram shows the space density of BSTHB HVCs if they are put at the critical radii for gravitational stability. The unshaded histogram shows the effect of a baryon-to-total mass ratio \( f \) varying from cloud to cloud. The lighter shaded histogram corresponds to BB HVCs, all at the same distance of 1 Mpc. The lines are the same as in top panel. *Third panel:* HiMFs for BSTHB HVCs for different values of \( f \) (from right to left: \( f = 0.2, 0.1, 0.05, 0.025, \) and 0.0125). The HVC HiMF is consistent with the field HiMF if \( f \leq 0.02 \) and if the median distance is \( \leq 200 \) kpc. **Bottom panel:** Distribution of the expected \( \text{HI} \) detections in the AHiSS for the BSTHB population. The light-gray histogram corresponds to clouds surrounding galaxies, and the dark gray histogram represents clouds in galaxy groups (see § 4 for explanation).
4. EXPECTED NUMBER OF EXTRAGALACTIC HVC DETECTIONS

The AHiSS, which is discussed in detail in Sorar (1994) and Zwaan et al. (1997), puts limits on the space density of primordial gas clouds in external galaxy groups and around galaxies. The survey was taken in drift-scan mode and consists of two strips at constant declinations, together covering 20 hr of right ascension over a redshift range from 0 to 7500 km s$^{-1}$. The limiting column density was $10^{18}$ cm$^{-2}$, which is lower than that of most of the HVCs in the WW compilation and those present in BB. The sky coverage is small (15 deg$^2$ excluding the side lobes), but the survey strip passes through the halo regions of many groups and galaxies, as shown in Figure 2. Therefore, the unique character of this survey makes it more suitable than other surveys of equal size for assessing the HVC problem. From the Lyon-Meudon Extragalactic Database (LEDA), we selected all known galaxies with projected distances less than 1 h$_{65}^{-1}$ Mpc from the two AHiSS strips. The circles in Figure 2 indicate shells with 1 Mpc radii around the galaxies. Since the discussion in BSTHB is primarily focused on galaxy groups, we also selected all cataloged groups within 1 Mpc of the strips. Galaxy groups were drawn from Willick et al. (1997), who used the Mark III catalog, and Garcia (1993), who selected groups from the LEDA galaxy sample.

We fill the volumes around the selected groups and galaxies with a synthetic population of HVCs similar to the one proposed in BSTHB. To construct such an ensemble, we make use of the compilation of HVCs by WW as discussed in § 3. Although BSTHB put particular emphasis on galaxy groups, we choose to consider clouds around individual galaxies as well. Hierarchical formation scenarios do not distinguish between galaxies and groups in the relative number of satellites (Klypin et al. 1999). Further motivation comes from the fact that in the LG, subclustering of dwarfs is observed around the Milky Way and M31 (Mateo 1998).

The 3$'$ beam of the Arecibo telescope subtends $d_{\text{beam}} = 0.87D$ kpc at a distance $D$ Mpc. The typical size of an HVC discussed in BSTHB is 28 kpc, and therefore the lowest column density clouds could be detected out to distances of 32 Mpc, beyond which the average HVC would no longer fill the beam. HVCs with column densities in excess of the limiting value of $10^{18}$ cm$^{-2}$ could be detected to larger distances. The limiting column density for clouds at large distances for which $d_{\text{cloud}} < d_{\text{beam}}$ is $N_{\text{lim}} = 10^{18}(d_{\text{beam}}/d_{\text{cloud}})^2$. For each group and galaxy, a fraction of the volume of the surrounding sphere is scanned by the Arecibo beam. The number of clouds within that volume is calculated, taking into account the column densities and sizes of the individual clouds.

Table 1 lists the number of clouds that would have been detected in the Arecibo H$\text{I}$ strip survey if a population of extragalactic HVCs existed with the BSTHB properties. We calculate the numbers of clouds differently for groups and for galaxies. Since BSTHB do not specify the exact radial distribution of clouds, we tested three different radial distribution functions to fill the volumes with clouds: (1) a spherical volume of radius $R$, (2) a thin spherical shell of radius $R$, and (3) a thick spherical shell with clouds distributed according to a...
TABLE 1

| HOSTS   | Uniform | Shell | Gaussian | BB | SELECTED |
|---------|---------|-------|----------|----|----------|
| Groups  | 70(52)  | 72(54) | 70(52)  | 9(8)| 14       |
| Galaxies| 248(167)| 256(173)| 268(177)| 39(28)| 347      |

Note.—The number of expected HVC detections are calculated assuming a 5 \( \sigma \) detection threshold. The numbers in parentheses indicate the expected number of groups and galaxies that are included in the analysis. For the Gaussian distributions, a selection radius of 2 Mpc has been used for inclusion in the sample.

TABLE 2

| HOSTS   | Ultralarge | Large   | Intermediate | Small |
|---------|------------|---------|--------------|-------|
| Groups  | 300        | 150     | 75           | 37    |
| Galaxies| 1000       | 500     | 250          | 125   |

Note.—The number of expected HVC detections are calculated assuming a 5 \( \sigma \) detection threshold. The numbers in parentheses indicate the expected number of groups and galaxies that are included in the analysis. For the Gaussian distributions, a selection radius of 2 Mpc has been used for inclusion in the sample.

5. CONCLUSIONS

The hypothesis that HVCs are primordial gas clouds with typical H 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. Blind H I surveys of the extragalactic sky would have detected these clouds if they existed around all galaxies or galaxy groups in numbers equal to those suggested for the Local Group. These results are highly significant: the Arecibo H I strip survey would have detected approximately 250 clouds around individual galaxies and 70 in galaxy groups.

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