Gas Rich Dwarf Spheroidals

Leo Blitz

Timothy Robishaw

Astronomy Department, University of California, Berkeley, CA 94720; blitz@gmc.berkeley.edu; robishaw@gmc.berkeley.edu

ABSTRACT

We present evidence that nearly half of the dwarf spheroidal galaxies (dSph and dSph/dIrr) in the Local Group are associated with large reservoirs of atomic gas, in some cases larger than the stellar mass. The gas is sometimes found at large distance (∼10 kpc) from the center of a galaxy and is not necessarily centered on it. Similarly large quantities of ionized gas could be hidden in these systems as well. The properties of some of the gas reservoirs are similar to the median properties of the High-Velocity Clouds (HVCs); two of the HI reservoirs are catalogued HVCs. The association of the HI with the dwarf spheroidals might thus provide a link between the HVCs and stars. We show that the HI content of the Local Group dSphs and dIrrs exhibits a sharp decline if the galaxy is within 250 kpc of either the Milky Way or M31. This can be explained if both galaxies have a sufficiently massive x-ray emitting halo that produces ram-pressure stripping if a dwarf ventures too close to either giant spiral. We also investigate tidal stripping of the dwarf galaxies and find that although it may play a role, it cannot explain the apparent total absence of neutral gas in most dSph galaxies at distances less than 250 kpc. For the derived mean density of the hot gas, \( n_0 = 2.5 \times 10^{-5} \) cm\(^{-3}\), ram-pressure stripping is found to be more than an order of magnitude more effective in removing the gas from the dSph galaxies. The hot halo, with an inferred mass of \( 1 \times 10^{10} \) M\(_\odot\), may represent a reservoir of \( \sim 10^3 \) destroyed dwarf systems, either HVCs or true dwarf galaxies similar to those we observe now.

Subject headings: Local Group, galaxies: dwarf, interstellar medium, intergalactic medium, evolution
1. Introduction

Recently, Blitz et al. (1999) have shown that the HVCs, clouds of atomic hydrogen inconsistent with near-circular rotation about the Galactic Center, are well explained if they are members of the Local Group. A simple dynamical model can replicate both the observed distribution on the sky as well as the observed kinematics of the ensemble of the HVCs. In their paper, Blitz et al. (1999) made several predictions; among them are that HVCs have Hα surface brightnesses less than those measured in the Magellanic Stream, metallicities of 0.1 solar or less, and internal pressures $P/k \sim 1-10$ K cm$^{-3}$; the last of these is inferred from the self-gravity of HVCs. All of these predictions have been subsequently confirmed (Weiner et al. 2000; Wakker et al. 1999; Sembach et al. 1999). Only one set of observations now seems to present problems for the model: three deep, blind extragalactic H\textsc{i} surveys, two made at Arecibo (Zwaan et al. 1997; Spitzak & Schneider 1998), and one at Parkes (Banks et al. 1999).

If the HVCs are extragalactic and part of the Local Group, as Blitz et al. (1999) argue, then extragalactic analogues should be observable; many examples have indeed been reported in the literature (Blitz et al. 1999 and references therein). The blind H\textsc{i} surveys have also found many uncatalogued H\textsc{i} clouds, but on closer inspection, all but one of the detections are found to harbor galaxies, albeit often of very low surface brightness. Because stars have not been detected in HVCs, they have been assumed to be starless systems. No such systems have been found by either Zwaan et al. (1997) or Banks et al. (1999); and only one potentially starless system has been found in the Spitzak & Schneider (1998) survey. The sensitivity of both surveys appears to be high enough and the velocity coverage large enough, that at least a few HVC analogues should have been detected in these surveys.

On the other hand, it is unclear whether the lowest surface brightness galaxies found in the optical follow-up to the H\textsc{i} detections would have been detected if those systems were located in the Local Group. These galaxies, which compose a significant fraction of the Zwaan et al. (1997) and Spitzak & Schneider (1998) H\textsc{i} identifications, appear morphologically similar to the Local Group dwarf spheroidal galaxies, which have been observed to be generally gas-free (Mateo 1998). At Local Group distances such low surface brightness systems would be extended and relatively difficult to identify in existing surveys. However, with concerted searching, a number of dSph galaxies have recently been discovered in the Local Group (Whiting et al. 1997; Armandroff, Davies, & Jacoby 1998; Karachentsev & Karachentseva 1999; Gallart et al. 1999), suggesting that there might be similar, or even lower surface brightness galaxies associated with HVCs.

A search for low surface brightness galaxies in HVCs is currently underway, but as a first step, we decided to examine the newly discovered Local Group dwarfs for 21-cm
emission using the Leiden-Dwingeloo H\textsc{i} survey (LDS - Hartmann & Burton 1997) to see if any are associated with HVCs. After the detection of H\textsc{i} toward And V, and its subsequent identification as HVC 368 in the compilation of Wakker & van Woerden (1991), we decided to reexamine the H\textsc{i} content of all of the dSph galaxies in the Local Group; the results are presented in §3. We have found H\textsc{i} toward four galaxies in which it had not previously been detected, and found H\textsc{i} more extended than previously thought in two others. The H\textsc{i} found toward two galaxies are catalogued HVCs. In §4 we examine the implications of the H\textsc{i} observations and infer the existence of a hot gaseous corona around the Milky Way and M31 with a mean density of $\sim 2.5 \times 10^{-5} \text{ cm}^{-3}$. Rather than being gas-poor, the dSph galaxies are often gas-rich, but with rather extended H\textsc{i} envelopes.

2. Analysis

The sensitivity of the LDS is about 70 mK in a 1 km s\textsuperscript{-1} velocity channel; its angular resolution is 36\arcmin. The survey covers the entire northern sky down to a declination of -30\degree at a sampling interval of 30\arcmin. At a distance of 100 kpc, the beam is 1.05 kpc. Its effective velocity coverage of $-450 \leq V_{\text{LSR}} \leq +400$ km s\textsuperscript{-1} is sufficient to detect all Local Group emission down to a 5\sigma column density $N(\text{H})/(\Delta V)^{-1/2} = 6.4 \times 10^{17}$ cm\textsuperscript{-2} (km s\textsuperscript{-1})\textsuperscript{-1/2} averaged over the beam ($\Delta V$ is the full width at half maximum of the H\textsc{i} emission). The survey also has the virtue of having flat baselines which makes it possible to detect very low level emission at velocities away from the normal Galactic emission.

We initially examined a five point cross centered at the optical position of all of the galaxies catalogued as dSph or dSph/dIrr in the compilation of Mateo (1998), but excluded those also classified as dE or E systems because of their much higher surface brightness. We also examined the galaxies subsequently identified as possible Local Group dSph galaxies by Karachentsev & Karachentseva (1999) and Gallart et al. (1999) which could be found in the LDS. If a galaxy sits between grid points of the survey, we examined a somewhat larger area. A number of the galaxies were found to have 21-cm emission confined to a small area coincident with or very close to the dSph at velocities outside the range normally associated with Galactic emission.

One can estimate the probability of a chance coincidence of a dSph with a cloud along the line of sight from the surface filling fraction of small HVCs ($\leq 1$ deg\textsuperscript{2}) in the Wakker & van Woerden (1991) compilation. The HVCs comprise all of the H\textsc{i} emission not associated with galaxies outside the range of normal Galactic emission and have the same range of radial velocities as the dSphs. The total area on the sky of small HVCs is less than 300 deg\textsuperscript{2}, though this number is somewhat uncertain at the 50\% level because of the sparse sampling
of the Wakker & van Woerden (1991) catalogue. It is certainly an upper limit, though, based on the higher resolution mapping of about 20% of the smaller HVCs by Blitz et al. (1999) and by Braun & Burton (1999). The HVCs are spread all over the sky with some concentration in the general directions of the barycenter and antibarycenter of the Local Group, thus the probability of a chance coincidence with a cloud that subtends an angle of less than 1 deg$^2$ is $\lesssim 0.01$. Equivalently, a positional coincidence with such a cloud is significant at the $\gtrsim 2.5\sigma$ level. We therefore consider the likelihood of a chance coincidence of a dSph with a small HI cloud to be sufficiently low that it is indicative of a real physical association, even if no velocity is available for the galaxy. Indeed, in a sample of $\sim 20$ objects such as considered here, the probability of a chance positional coincidence of any dSph with an HI cloud is $\sim 0.2$, and the number of detections is about 50 times higher.

In the case where velocity information is available, the probability of an optical and HI velocity coincidence within $2\sigma$ of the HI velocity dispersion of $\sim 13$ km s$^{-1}$ (Blitz et al. 1999) is about 0.06 within the velocity range in which HVCs are detected: about 800 km s$^{-1}$. This probability must be increased somewhat because we consider only velocities outside the range of normal Galactic emission, but in the directions in which most dSphs are found, the Galactic emission is not wider than about 200 km s$^{-1}$. The joint probability of velocity and spatial coincidence is thus $\sim 10^{-3}$. Probabilities of chance coincidences can be estimated for individual galaxies and are done so where appropriate in the text.

If emission was found to be associated with a galaxy, based on positional coincidence alone, or where possible, joint position and velocity coincidence, we averaged all of the profiles where emission was evident. One or more Gaussians were then fit to the averaged spectrum in order to determine a central velocity and velocity extent of the emission. The maps are shown in Figure 1. The values of the central velocity, FWHM velocity extent, and brightness temperature of the Gaussian fits to the position-averaged spectra are listed in Table 1. The derived values for M(HI) and $\Omega$, the HI mass and the solid angle of the cloud, are not corrected for source convolution with the telescope beam. We then searched a $7^\circ \times 7^\circ$ area to see if the emission is localized around the target galaxy or whether it exists over a more extended area. In two cases, rather extended emission was found and the maps are shown in Figures 2 and 3. The individual maps are discussed in §3.1 below.

Some of the apparent detections were quite weak and Jay Lockman kindly observed some of these with the NRAO 140′ telescope$^1$ prior to its shutdown in late July 1999 to obtain confirmation. In most cases the observations were about 4 times longer than those of

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$^1$The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.
the LDS. The beam of the 140′ telescope is about 20′ at the frequency of the 21-cm line.

Finally, we searched the catalogues of Hulsbosch & Wakker (1988) and Wakker & van Woerden (1991) to see whether any of the HI clouds are catalogued HVCs. We found two such cases, the cloud associated with And V is HVC 368, and the cloud associated with Sculptor is HVC 561. LGS 3 had been previously detected at three positions and DDO 210 at one position on the 1°×1° sampling grid of Hulsbosch & Wakker (1988). The temperature-weighted mean Galactic latitude and longitude, as well as the HI column density and mass for each cloud can be found in Table 1. The derived HI masses assume that the emission is at the distance of the galaxy. The non-detections are listed in Table 2. The observed properties of the detected clouds are similar to one another and to the typical properties of HVCs, but are generally weaker than HI detections of Local Group dIrr, Irr, or spiral galaxies.

3. Results

We have made new HI detections toward And III, And V, Leo I and Sextans. In addition, the HI emission toward LGS 3, DDO 210, and Sculptor is found to be considerably more extended than previously thought.

In all, of 21 confirmed Local Group dSph galaxies, HI is detected in apparent association with 10 galaxies. Two galaxies are too far south to have been observed in the Leiden-Dwingeloo survey, and several probable non-detections are somewhat ambiguous. One galaxy previously reported as a detection, Antlia (Fouqué et al. 1990), is probably an instrumental artifact. There are 9 non-detections, not including the dE systems or the two unconfirmed candidate dSph galaxies of Karachentsev & Karachentseva (1999). Four galaxies are below the declination limit of the LDS, but two of these, Phoenix and Tucana, have been observed and detected in HI by others (Young & Lo 1997; Oosterloo et al. 1996); they are therefore included in the list of detections. Thus almost half of the confirmed Local Group dSph galaxies have been detected in HI, though only five of those detected have measured optical velocities as of this writing. Attempts are actively underway by several groups to obtain more velocities.

Two of the galaxies shown in Figure 1 exhibit emission close to, but not coincident with the target galaxy: Leo I and Sextans. This might explain why these two galaxies have not been previously detected in HI; and why the detection of HI toward Tucana by Oosterloo, Da Costa, & Stavely-Smith (1996) ought to be reinterpreted. These authors found a cloud very close to, but not coincident with Tucana, in which the highest column density emission is offset by about 15′ from the nucleus. Oosterloo et al. (1996) felt that the position offset
| Galaxy   | $l$   | $b$   | dist [kpc] | $L_{\text{V}}$ [10^6 L$_\odot$] | $V_{\text{LSR, opt}}$ [km s$^{-1}$] | $V_{\text{LSR, HI}}$ [km s$^{-1}$] | $T_B$ [K] | $\Delta V$ [km s$^{-1}$] | $(l)^a$ | $(b)^b$ | $N$(H$\text{I}$) [10^18 cm$^{-2}$] | $M_{\text{HI}}$ [10^6 M$_\odot$] | $\Omega_{\text{cloud}}$ [deg$^2$] |
|----------|-------|-------|------------|-------------------------------|----------------------------------|----------------------------------|--------|-----------------|--------|--------|-------------------------------|-----------------|-----------------|
| And III  | 119.3 | -26.2 | 760±40     | 1.13                          | -337±6                          | 0.02±0.02                       | 20±5   | 4               | 119.5 | -26.0 | 0.7                           | 16.4            | 3.1             |
| And V$^c$ | 126.2 | -15.1 | 810±45     | 0.36$^d$                      | -176±1                          | 0.09±0.01                       | 20±2   | 3.3             | 125.8 | -15.5 | 4.4                           | 11.8            | 1.9             |
| DDO 210  | 34.0  | -31.3 | 880±250    | 0.81                          | -131±1                          | 0.12±0.01                       | 18±2   | 3.5             | 34.7  | -31.8 | 4.0                           | 11.8            | 3.1             |
| Leo I    | 226.0 | 40.1  | 250±30     | 4.79                          | 251±2                           | 0.05±0.01                       | 50±5   | 4.4             | 226.2 | 49.4  | 127.7                         | 10.4            | 1.3             |
| LGS 3    | 126.8 | -40.9 | 810±60     | 1.33                          | -331±3                          | 0.06±0.01                       | 46±7   | 5.1             | 195.0 | -43.6 | 6.9                           | 10.4            | 1.3             |
| Pegasus  | 94.8  | -43.5 | 955±50     | 12.0                          | -180±2                          | 0.09±0.01                       | 25±5   | 4.1             | 95.0  | -43.6 | 127.7                         | 10.4            | 1.3             |
| Phoenix$^e$ | 272.2 | -68.9 | 445±30     | 0.90                          | -34±3                           | 1.40±0.17$^f$                    | 16±3   | 4.9             | 235.9 | 59.2  | 5.1                           | 0.04            | 0.01            |
| Sculptor | 287.5 | -83.2 | 79±4       | 2.15                          | 100±3                           | 0.14±0.03                       | 20±5   | 5.1             | 286.9 | -83.5 | 0.69                          | 1.2             |                 |
| Sextans  | 243.5 | -42.3 | 86±4       | 0.50                          | 221±3                           | 0.05±0.01                       | 34±12  | 3.1             | 244.7 | 42.5  | 0.03                          | 0.5             |                 |
| Tucana$^g$ | 322.9 | -47.4 | 880±40     | 0.55                          | 125±2                           | 0.56±0.14$^b$                    | 24±7   | 1.5             | 322.9 | 47.6  | 78                            |                 |                 |

\(^a,b\) Mean Galactic longitude and latitude, respectively, of H$\text{I}$ emission, calculated by weighting each position with temperature.
\(^c\) $l$, $b$ & distance from Armandroff, Davies, & Jacoby (1998).
\(^d\) $L_{\text{V}}$ from Armandroff, Jacoby, & Davies (1999).
\(^e\) Data for Phoenix are taken from Young & Lo (1997).
\(^f\) Peak brightness temperature with rms noise of 0.17 K.
\(^g\) Data for Tucana are taken from Oosterloo, Da Costa, & Staveley-Smith (1996).
\(^h\) Oosterloo (private communication)
\(^i\) Velocity resolution is 7 km s$^{-1}$. 
implied that the H\textsubscript{I} cloud and the galaxy are unrelated. We show in the next section, however, that the relationship between the H\textsubscript{I} cloud and Tucana is similar to other galaxies in our sample, particularly Leo I, in which the velocity of the H\textsubscript{I} and the galaxy are both measured and found to be in close agreement. We therefore include Tucana in Table 1 as a detection.

3.1. Comments on Individual Detections

3.1.1. And III

And III is a rather problematic H\textsubscript{I} detection. It appears to be clearly detected in the LDS (see Figure 1), and a confirmation spectrum of the galaxy taken with the 140′ telescope showed a much weaker component at low significance at the same velocity. The weakness of the 140′ spectrum is rather surprising, however, given the smaller beam and the longer integration time. The detection, nevertheless, does appear to be real, though of low significance. A measurement of the optical velocity of the galaxy or a deep H\textsubscript{I} integration over the LDS beam will confirm or refute this detection. The values given in Table 1 are from the deeper 140′ observations.

(NB: The referee, Mario Mateo, has pointed out that the optical velocity of this galaxy has recently been determined by Côté, Mateo, & Sargent (2000), and is within 1σ of the combined H\textsubscript{I} and optical velocity uncertainties).

The H\textsubscript{I} non-detection reported by Thuan & Martin (1979) is for a 4′ beam at Arecibo centered on the galaxy. The H\textsubscript{I} mass given in Table 1 is consistent with their upper limits, particularly if the H\textsubscript{I} is not centered directly on the dSph, as is the case for several other galaxies.

3.1.2. And V

This is an intriguing case not only because of the apparent association of the H\textsubscript{I} with the galaxy, but also because the H\textsubscript{I} is listed as HVC 368 in the compilation of Wakker & van Woerden (1991). Thus a measurement of the radial velocity of the galaxy that agrees with the H\textsubscript{I} velocity would provide the second firm association of an HVC with a dSph (see the discussion of Sculptor below). As shown in Figure 2, however, HVC 368 lies quite close to HVC 287, also known as complex H. The latter has an angular extent of \(\sim205\ \text{deg}^2\), and a velocity similar to HVC 368. Blitz et al. (1999) have argued that complex H lies beyond the
Fig. 1.— Maps of the velocity-integrated H\textsc{i} emission associated with Local Group dSphs from the Leiden-Dwingeloo survey. Below each map is a spectrum of the emission averaged within the lowest contour of each map. The position of the galaxy is given by the crossed circle. The lowest contour is 1.5 times the uncertainty of the velocity integrated brightness temperature; the contour interval is 1/6 of the difference between the first contour and the maximum value of the map. The spectra have been smoothed to 4.1 km/s resolution for easier viewing. The arrow gives the velocity centroid of the spectrum in each panel.
Fig. 1 (cont.).— The dark line shown for Sculptor is the lower declination limit of the LDS. A complete map is shown in Carignan (1999).
\~40 kpc radius of the H\textsc{i} disk of the Galaxy, but probably not far beyond. The proximity of the two clouds and the similarity of their radial velocities suggests that the smaller cloud may be a fragment of the larger one, and may thus be an unrelated foreground object. In that case, the probability of a chance coincidence is much higher than the value of $\sim 10^{-2}$ for the other dSph galaxies. We present additional arguments in §4 why this H\textsc{i} cloud might be a chance superposition. A measurement of the optical velocity would clearly determine whether the H\textsc{i} and the galaxy are associated.

Fig. 2.— H\textsc{i} along the line of sight to And V. It is unclear whether HVC 368 is a fragment of HVC 287 or is a truly independent object. The blob of emission at $l = 122^\circ$, $b = -21^\circ$ is H\textsc{i} associated with M31.

### 3.1.3. DDO 210

The H\textsc{i} in this galaxy was previously observed by Lo, Sargent, & Young (1993) at the VLA, and the mass we obtain for the H\textsc{i} emission centered on the galaxy is in good agreement with theirs, correcting for the different distances assumed. Note, however the additional emission seen in Figure 1 that is outside the Lo et al. (1993) field of view. The relatively strong emission seen at $l = 35^\circ$, $b = -32^\circ$ is a narrow component at nearly the same velocity as the galaxy. The low level disconnected emission in Figure 1 may not be real, but the H\textsc{i} cloud associated with DDO 210 nevertheless appears to be considerably larger than that observed by Lo et al. (1993).
3.1.4. Leo I

There is a clear detection of an H\textsubscript{I} cloud with a large velocity dispersion in the direction of this galaxy at a velocity close to, but slightly shifted from the velocity of the dSph. The uncertainty in the velocity of the line center is, however, relatively large and the width of the line comfortably encompasses the velocity of the galaxy. We show two maps in Figure 3. On the left is a map of the brightness temperature distribution over the full width of the H\textsubscript{I} line. The map shows the extent of what appears to be highly fragmented H\textsubscript{I} emission; a larger map (not shown) indicates that this emission is confined to the area shown in the panel. As a check, we produced a map over the same area within $\pm 10$ km s$^{-1}$ of the Leo I optical velocity shown in the right hand panel of Figure 3. The H\textsubscript{I} in this velocity range is confined to an area quite close to the galaxy, but surprisingly, no H\textsubscript{I} is seen directly toward the galaxy itself. The full velocity extent of the H\textsubscript{I} is much more extended, and is seen over an area of about 10–20 deg$^2$. Nevertheless, since the H\textsubscript{I} in the velocity range of Leo I is so closely confined to the environs of the galaxy, it seems likely that all of the H\textsubscript{I} is at the distance of the dSph. Higher resolution H\textsubscript{I} mapping might make the association clearer.

The H\textsubscript{I} non-detection reported by Knapp, Kerr, & Bowers (1978) was made with a single pointing of the 300 ft (91 m) telescope at Green Bank and a 10$'$ beam; it is consistent with the present detection.

Fig. 3.— Leo I. (Left) Moment map for $237 \leq V\textsubscript{LSR} \leq 277$ km s$^{-1}$, covering the FWHM velocity of the Gaussian fit to the position-averaged profile. (Right) Moment map for $271 \leq V\textsubscript{LSR} \leq 292$ km s$^{-1}$ which covers the radial velocity of the galaxy $\pm 10$ km s$^{-1}$. 
3.1.5. **LGS 3**

The H\textsc{i} cloud in the vicinity of LGS 3 was noted by Hulsbosch & Wakker (1988) and is quite close to the galaxy, but the velocity centroid of most of the H\textsc{i} differs from that of the galaxy by about 50 km s$^{-1}$. This galaxy was mapped with the VLA by Young & Lo (1997) who found an H\textsc{i} cloud centered on the dSph within a few km s$^{-1}$ of the velocity of LGS 3 and a total H\textsc{i} mass of $4 \times 10^5$ M$_\odot$. Smoothing of the LDS H\textsc{i} profile at the position of the galaxy shows both the -285 km s$^{-1}$ component and a component centered at about -340 km s$^{-1}$. A hint of the more extreme velocity can be seen in the 140$'$ spectrum shown by Young & Lo (1997). The probability of two HVCs seen along the same line of sight that are this compact is about $10^{-2}$ (see §2). While the large velocity difference between the cloud shown in Figure 2 and the cloud mapped by Young & Lo (1997) is puzzling, the relation of the dSph to the cloud bears some resemblance to the other systems pictured in Figure 1. We discuss in §4 the possibility that the more negative velocity component may result from ram-pressure stripping.

Although the emission detected by Young & Lo (1997) is not seen in either the map or the spectrum shown in Figure 1, both are consistent with their detection. The peak flux density of this galaxy observed at the 140$'$ telescope is about 110 mJy, corresponding to an expected antenna temperature of 0.021 K when observed with the Dwingeloo telescope. This is the strength at which the feature is seen, within the noise, in the LDS at the position of the galaxy. The spectrum shown in Figure 1 is an average of 6 positions at which the galaxy is detected; the expected peak temperature of that feature is lowered by yet another factor of 2.5; a feature of that strength is too weak to be detected. Both the spectrum and the map of this source are consistent with the observations of Young & Lo (1997).

3.1.6. **Pegasus**

Pegasus has been previously mapped by Lo, Sargent, & Young (1993). The mass obtained with the LDS data is in reasonable agreement with that of Lo et al. (1993) when account is taken of the different distances assumed and the possibility that some of the flux may be missed with the VLA observations.

3.1.7. **Phoenix**

Although this galaxy is too far south for the LDS, it has previously been mapped by Carignan, Demers, & Côté (1991), Young & Lo (1997) and St-Germain et al. (1999). Because
this galaxy lies close to the main emission from the Milky Way, and its optical velocity has
not yet been measured, it is unclear which of two relatively compact velocity components,
if either, is associated with the galaxy. The HI properties listed in Table 1 are from St-
Germain et al. (1999). They cite evidence suggesting that the lower mass (i.e. \( 2 \times 10^5 \)
M\(_\odot\)) HI component is associated with the galaxy, in part because they find the larger mass
component implausibly large. We follow their suggestion and use the lower value in Figure 4
below. Without a reliable single dish map however, it is unclear whether the interferometer
recovers all of the flux associated with the galaxy. Thus the mass quoted by St-Germain et
al. (1999) should be considered a lower limit.

3.1.8. Sextans

Although the emission from Sextans shown in Figure 1 is not centered on the galaxy, the
velocity of the HI emission is quite close to the optical velocity. The probability of a cloud
outside the galaxy with a velocity within \( \pm 15 \) km s\(^{-1}\) of the galaxy is about 0.05. The joint
probability of a small cloud within 4 square degrees with a velocity outside of the normal
Galactic emission in such close agreement with the optical velocity is about \( 1.5 \times 10^{-3} \). The
cloud shown in Figure 1 is therefore probably associated with the galaxy; the edge of the HI
cloud is only about 1 kpc from the galaxy in projection.

3.1.9. Sculptor

Sculptor is a particularly interesting case because of the two-lobed HI structure found by
Carignan et al. (1998) and because the HI emission associated with the galaxy is catalogued
as HVC 561 in the compilation of Wakker & van Woerden (1991). The map of the galaxy
shown in Figure 1 is incomplete because the galaxy is beyond the southern declination limit
of the LDS. Carignan et al. (1998) were at pains to point out that the HI emission in their
map might only be a small fraction of the total because of the spatial filtering of their
interferometric observations, and because the HI extends to the limit of the spatial scale
to which their observations are sensitive. A more complete map was recently published
by Carignan (1999) using the Parkes 43-m telescope showing that the HI associated with
Sculptor has an extent of about 2°, larger than that shown in Figure 1, but the total mass is
not given. The mass given in Table 1 is from the LDS, but may be low by a factor of about
2-3.
3.1.10. Tucana

Tucana is below the southern declination limit for the LDS, but was observed at the ATNA by Oosterloo, Da Costa, & Staveley-Smith (1996), who found an H\textsc{i} cloud close to, but not quite coincident with the galaxy. The centroid of the emission is located only 15' from the galaxy and some of the emission is as close as 1' from it. The joint probability of such close agreement in position and velocity between the observed H\textsc{i} and the optical galaxy is about $10^{-4}$, suggesting that the H\textsc{i} cloud is indeed bound to the galaxy. Furthermore the Oosterloo et al. (1996) observations were done with the ATNA, and the map extends over a large fraction of the beam. It is therefore likely that the extent of the H\textsc{i} emission is larger than that shown in their map, similar to what is observed in Sculptor. The relationship of the H\textsc{i} to the optical galaxy in this case is similar to galaxies such as Leo I, And V, Sculptor and possibly LGS 3. The low probability of a chance superposition, together with the similarity to other systems, suggests that the H\textsc{i} is indeed related to Tucana. If the cloud is at the distance of the dSph, it has a mass of $1.5 \times 10^6 M_\odot$.

3.2. The Non-Detections

A number of the non-detections are somewhat ambiguous because the optical velocity of the galaxy is close to the Galactic H\textsc{i} emission, or because a feature of marginal significance is present in the LDS. High significance non-detections were made toward And II, Leo II and And VII using the 140' telescope with an rms noise temperature of about 35 mK in 1 km s$^{-1}$ channels. The non-detection toward Leo II is consistent with that of Young (1999).

A reported detection of Antlia by Fouqu{é} et al. (1990) could not be reproduced, and is probably part of the emission from NGC 3109 entering a sidelobe of the telescope. We were unable to see any evidence for emission in the LDS at the position observed by these authors.

4. Discussion

The detection of H\textsc{i} associated with many dSph galaxies suggests that rather than being gas-free systems, perhaps half of them are in fact gas-rich galaxies, with H\textsc{i} that is a substantial fraction of the luminous mass, $M_L$, and in some cases exceeding it. If we take $M_L/L_V = 1-2$ in solar units, then more than half of the galaxies in Table 1, about 25% of all of the dSphs, have H\textsc{i} masses in excess of 50% of the luminous mass of the galaxy. Most previous observations have concentrated on searching for H\textsc{i} only at the central position of a
Table 2. Local Group Dwarf Spheroidals Undetected in the LDS

| Galaxy        | $l$   | $b$   | dist [kpc] | $V_{LSR,opt}$ [km s$^{-1}$] |
|---------------|-------|-------|------------|-----------------------------|
| And I         | 121.7 | -24.9 | 805±40     | ...                         |
| And II$^a$    | 128.9 | -29.2 | 525±110    | -188±3                      |
| And VI$^b$    | 106.0 | -36.3 | 775±35     | ...                         |
| And VII$^c$   | 109.0 | -10.1 | ...        | ...                         |
| Antlia        | 263.1 | 22.3  | 1235±65    | ...                         |
| Leo II        | 220.2 | 67.2  | 205±12     | 77±2                        |
| Ursa Minor    | 105.0 | 44.8  | 66±3       | -237±2                      |
| Draco         | 86.4  | 34.7  | 82±6       | -279±2                      |
| Sagittarius   | 5.6   | -14.1 | 24±2       | 148±5                       |
| KK99 191.1    | 109.0 | -3.6  | ...        | ...                         |
| KK99 348.1    | 109.1 | -22.4 | ...        | ...                         |

Local Group Dwarf Spheroidals Outside Observed Region of LDS

| Galaxy       | $l$   | $b$   | dist [kpc] | $V_{LSR,opt}$ [km s$^{-1}$] |
|--------------|-------|-------|------------|-----------------------------|
| Carina       | 260.1 | -22.2 | 101±5      | 209±3                       |
| Fornax       | 237.1 | -65.7 | 138±8      | 41±3                        |

$^a$Radial velocity from Côté et al. (1999)

$^b$l, $b$ & distance from Armandroff, Davies, & Jacoby (1998)

$^c$l, $b$ from Karachentsev & Karachentseva (1999)
galaxy largely because the beam of the HI observations was as large or larger than the galaxy itself. The observations presented here show that sometimes the HI avoids the nucleus of the galaxy and is seen over a large area around it (e.g. Leo I).

With the exception of And V, there is little doubt that the HI clouds shown in the maps in Figure 1 are associated with the galaxies, even though optical radial velocities are not available for most dSphs. As discussed in §2, the probability of a chance superposition with an HI cloud is quite small, typically about 0.01, and if a velocity is available, the probability is $< 10^{-3}$.

If all of the galaxies shown in Table 1 have ionized hydrogen masses equal to that of their atomic hydrogen, and if the HI were smoothly distributed out to the same radius as the HI, the typical emission measure except for Phoenix and Tucana would be $10^{-3} - 10^{-4}$ cm$^{-6}$ pc, more than an order of magnitude below what is currently detectable. Thus the dSphs might harbor substantial quantities of ionized gas in addition to what is shown in Figure 1.

We might reasonably ask why some of the dSph galaxies have large, massive HI envelopes (such as Leo I), why some have relatively wimpy HI envelopes (such as Sextans and Sculptor), and why some seem to be devoid of HI entirely (such as Ursa Minor and Draco). To approach this question, we have plotted the the HI mass of each of the dSph and dIrr galaxies in the Local Group as a function of the distance from the nearest giant spiral, either M31 or the Milky Way (MW) in Figure 4a. The data for the dIrr galaxies are taken from Mateo (1998).

Figure 4 shows a rather remarkable effect. With the exception of And V, no galaxy within 250 kpc of either M31 or the MW has an HI mass in excess of $10^6$ M$_\odot$; beyond 250 kpc almost all of the dwarf galaxies have substantial HI envelopes in excess of $10^6$ M$_\odot$, regardless of whether the galaxies are dSph or dIrr. Inside the 250 kpc cutoff most of the upper limits and the three detections are in fact below $10^5$ M$_\odot$. The one exception is And V which is the galaxy most likely to be a chance superposition (see §3.1.2). Antlia and Phoenix are the exceptions beyond the 250 kpc cutoff. Antlia may be anomalous because of its close proximity to NGC 3109. The HI mass of Phoenix may be underestimated since its mass is determined from an interferometric measurement confused by bright foreground emission at the same velocity. It is also possible that another more massive HI component is actually associated with the galaxy (§4.1.7).

To check whether the effect seen in Figure 4a might be a distance effect related to the Malmquist bias, we replotted the figure by normalizing to the visual luminosity of each galaxy, $L_V$, taken from Mateo (1998); the results are shown in Figure 4b. Evidence for the 250 kpc HI cutoff remains quite strong in this plot. Van den Bergh (1999a) noted that
Fig. 4.— (a) Plot of the H\textsc{i} masses of the Local Group dSphs and dIrrs vs. distance from the center of M31 or the Milky Way, whichever is closer. (b) Same as (a) except that the H\textsc{i} mass is normalized by the the V-band luminosity in solar units.
the dSph galaxies tend to be closer to M31 and the Milky Way than the dIrr galaxies, but because some of the galaxies beyond the 250 kpc H\textsc{i} cutoff are dSphs, the segregation in H\textsc{i} properties is not simply a function of morphological type. The sharp cutoff implies that some process strips the galaxies with perigalacticons $< 250$ kpc of their H\textsc{i}, a suggestion first made by Einasto et al. (1974) and later by Lin & Faber (1983). We investigate the relative importance of ram-pressure stripping and tidal stripping below.

### 4.1. Ram-Pressure Stripping

If the sharp boundary at $250$ kpc is due to ram-pressure stripping by hot halo gas (Gunn & Gott 1972), one can estimate the density of the ambient gas responsible for the stripping, $\rho_0$, from

$$ \rho_0 > \alpha G \Sigma_* \Sigma_g / V^2, $$

where $\Sigma_*$ and $\Sigma_g$ are the the stellar and gas surface densities respectively in the dwarf galaxy, $V$ is the velocity of the galaxy through the hot halo gas, and $\alpha$ is a constant near unity that depends on whether the galaxy is a flattened or a spheroidal system, and on the functional form of the gravitational potential. For a uniform spherical stellar system with an extended uniform density halo, $\alpha = \pi/6$. $\Sigma_*$ and $\Sigma_g$ in this case are the peak values measured at the center of the galaxy. The inequality exists because the gas may be clumped and the surface filling fraction of the H\textsc{i} may be less than unity, raising the local value of $\Sigma_g$ above its beam averaged value. If the gravitational mass of the galaxy, $M_*$, is given by $Rv_{3D}^2 / G$, then we may rewrite Equation 1 as:

$$ \rho_0 > \frac{\Sigma_g v_{3D}^2}{4RV^2}. $$

In terms of observables, Equation 2 may be rewritten as

$$ n_0 > 1.12 \times 10^{-4} \frac{T_B(\Delta V)^3}{RV^2} \text{ cm}^{-3}, $$

where $n_0$ is the number density of the hot halo gas, $T_B$ is the peak brightness temperature of the H\textsc{i}, and $\Delta V$ is the measured full width at half maximum of the H\textsc{i} line. We use this equation to estimate $n_0$. For $V$ we take the one-dimensional velocity dispersion of $60$ km s$^{-1}$ for the Local Group dwarf galaxies (van den Bergh 1999a). For $\Delta V$, we take the mean value for the galaxies from Table 1 of $25$ km s$^{-1}$. For $R$, we take it equal to $R_g$, the radius to which gas is observed in a dwarf galaxy; it ranges from about 1 - 10 kpc for all of the galaxies in the sample with the larger values all outside the 250 kpc cutoff radius. Inside the cutoff radius, three galaxies, And III, Sculptor and Sextans, still have associated H\textsc{i}, and we take $R = 2$ kpc, the largest of the radii to which gas is observed. Thus $n_0 \gtrsim 2.4 \times 10^{-5}$
Interestingly, this value is close to the value of $\sim 5 \times 10^{-5} \text{ cm}^{-3}$ derived by Moore & Davis (1994) for ram-pressure stripping of the Magellanic Clouds. Their value applies to the density of a hot halo at a distance of 65 kpc from the Galactic Center, whereas ours is an average over a volume of 250 kpc radius.

If the hot gas is in virial equilibrium and the mass of the MW is $1 - 1.5 \times 10^{12} \text{ M}_\odot$, the hot gas temperature is $\sim 1 - 1.4 \times 10^6 \text{ K}$, and the thermal pressure $P/k = 23 - 34 \text{ K cm}^{-3}$. The total mass of the hot halo at the derived $n_0$ is about $1 \times 10^{10} \text{ M}_\odot$ to 250 kpc.

Gas will be stripped from the galaxy if the column density of hot gas is equal to the column density in the galaxy. Thus for galaxies (or HVCs) with $N(\text{H} I) > n_0 \times 250 \text{ kpc} = 1.8 \times 10^{19} \text{ cm}^{-2}$, the gas can remain in the galaxy until it collides with the MW. The most recent map of Sculptor by Carignan (1999) shows H$\text{I}$ contours ranging from $0.15 - 2.4 \times 10^{19}$ cm$^{-2}$, but with a broad emission plateau of about $0.6 \times 10^{19}$ cm$^{-2}$, somewhat below the ram-pressure limit. The discrepancy, while not large, may be due to clumping (implying higher mean column densities within the beam), a somewhat high estimate for $n_0$, Sextans not having traversed a full 250 kpc in its orbit through the hot halo, or some combination of the three. The radial velocity of Sculptor relative to the Galactic Standard of Rest (GSR) is 75 km s$^{-1}$, close to the value of 60 km s$^{-1}$ assumed.

### 4.2. Tidal Stripping

Gas will be tidally stripped from a galaxy if

$$\frac{GM}{R^2} > -\frac{d}{dr} \left( \frac{\Theta^2}{r} \right) R,$$

where $r$ is the distance from the MW or M31 to the galaxy, and $\Theta$ is the circular speed of the MW or M31 at the distance of the dwarf galaxy. At a distance of 250 kpc, $\Theta = 130$ km s$^{-1}$ (appropriate for an enclosed MW mass of $1 \times 10^{12} \text{ M}_\odot$); the tidal radius of a dwarf galaxy with a total mass of $1 \times 10^8 \text{ M}_\odot$ is about 11.5 kpc, greater than the largest radius to which H$\text{I}$ is detected in any Local Group dwarf. Thus for these parameters, the gas is tidally stable. For dwarf galaxies at 80 kpc from the MW, the distance of Sculptor and Sextans, the tidal radius is about 4 kpc, comfortably larger than the $1.5 - 2$ kpc to which H$\text{I}$ is detected in either Sculptor or Sextans. Thus, the gas in these galaxies is tidally stable at their current distance, but if their perigalacticon is significantly smaller, then even the present day observed gas could be tidally stripped from these galaxies. Thus tidal stripping can be important in removing the outer H$\text{I}$ envelopes of the dSph galaxies within 250 kpc of the MW and M31.
Nevertheless, most of the dSphs within 250 kpc are devoid of H\textsubscript{I} to the current limits of detectability. While Galactic tides can be important in stripping the outermost H\textsubscript{I} layers of Local Group dSphs, it is difficult to understand how tidal stripping can completely rid a dSph of its atomic gas.

It is instructive to compare the effect of tidal vs. ram-pressure stripping in a dwarf galaxy at a radius of 10 kpc and located at a distance of 250 kpc from the MW. The tidal acceleration from Equation 4 above is \(R\Theta^2/r^2\). The acceleration of a parcel of gas due to ram-pressure is

\[
\frac{\rho_0 V^2}{\Sigma_g} = \frac{\rho_0 V^2}{N(H\textsubscript{I})\mu m\textsubscript{H}},
\]

where \(\mu\) is the mean mass per nucleon of the atomic gas. For \(\Theta = 130\) km s\(^{-1}\), \(n_0 = 2.5 \times 10^{-5}\) cm\(^{-3}\), and \(N(H\textsubscript{I}) = 5 \times 10^{18}\) cm\(^{-2}\), a typical value in the outskirts of Leo I and LGS 3, the ratio of the ram-pressure acceleration to the tidal acceleration is about 18. Tidal stripping becomes relatively more important, however, as one gets closer to the center of the Local Group giant spirals, but if there is even one tenth the density of hot gas around the MW and M31, as we derive above, ram-pressure stripping will be relatively more important than tidal stripping unless perigalacticon is very small.

We therefore conclude that although tidal stripping may play a role in the gas depletion of the dwarf galaxies in the Local Group, tidal stripping alone cannot explain the near total absence of atomic gas in most of the dSphs within 250 kpc of either the MW or M31. Ram-pressure stripping is much more efficient over most of the parameter space permitted by the H\textsubscript{I} observations, and implies that the MW and M31 have hot halos with radii of \(\sim 250\) kpc, beyond which stripping is ineffective.

It is quite reasonable that the MW and M31 have hot halos in the context of the Blitz et al. (1999) picture of the formation of the Milky Way and M31 from the accretion of HVCs. The dynamical model presented by these authors is quite simple and does not include collisions between HVCs which are expected close to either galaxy or in the region between the galaxies. Such collisions are, however, expected; the typical center-of-mass collision velocity is about 100 km s\(^{-1}\) at the present epoch, high enough to completely ionize the colliding clouds and to raise their temperatures to \(\sim 10^5\) K (McKee & Hollenbach 1980). Collisions between clouds at the present epoch are, however, expected to be rare, but should have been more frequent in the early universe (see Fig. 16 in Blitz et al. 1999). The typical cloud collision velocity at those times would have been higher, leading to hot gas temperatures which can reach the virial values. The cooling time of the hot halo gas at the present epoch is \(\sim 3 \times 10^{10}\) yr at an inferred mean density of \(2.5 \times 10^{-5}\) cm\(^{-3}\). Thus the hot halo gas is stable for more than a Hubble time, but the inner parts can cool and
condense in a shorter time if the density distribution is isothermal. Whether HVC collisions are frequent enough to produce a hot halo can be tested by direct numerical simulations. The halos around each galaxy need not be separate entities and may be connected along the line between the two galaxies.

The existence of a hot halo is consistent with the destruction of \( \sim 1000 \) objects with \( \text{H} \text{I} \) content of \( \sim 10^7 M_\odot \), close to the typical mass derived by Blitz et al. (1999) for the HVCs. It is worth noting that Klypin et al. (1999) have shown that simulations of hierarchical structure formation seem to require about 1000 dwarf galaxies to have formed in the Local Group, one and a half orders of magnitude more than have currently been identified. Klypin et al. (1999) suggested that the required number of dwarfs might be consistent with the inferred population of HVCs, but it is also possible that the gaseous halo is from a population of true dwarf galaxies with a typical \( \text{H} \text{I} \) content similar to that found in the present-day dwarfs that have been destroyed by collisions. A mass of \( 10^{10} M_\odot \) of hot gas would be provided by about \( 10^2 - 10^4 \) dwarf galaxies, with typical \( \text{H} \text{I} \) masses between \( 10^6 - 10^8 \), the range of \( \text{H} \text{I} \) masses in present-day dwarfs not yet stripped of \( \text{H} \text{I} \). The mean free path for collisions between HVCs ought to be smaller than that for dwarfs because of their larger diameters, and the difference between the two cases might be testable by simulations.

4.3. The Velocity Anomalies of LGS 3 and Leo I

One of the more difficult of the \( \text{H} \text{I} \) observations to understand is that of LGS 3, and to a lesser extent, Leo I. LGS 3 has an \( \text{H} \text{I} \) cloud clearly associated with it, but the \( \text{H} \text{I} \) cloud differs in velocity from the galaxy by 50 km s\(^{-1}\). The observations of this galaxy by Young & Lo (1997) show a well-defined \( \text{H} \text{I} \) component centered on the galaxy with a velocity essentially identical to the systemic velocity of the stars. The extent of the gas centered on the galaxy is only about 5′ compared to the extent of about 1.5′ in Figure 1. With a velocity difference of 50 km s\(^{-1}\), the gas shown in Figure 1 cannot be gravitationally bound to LGS 3, which suggests a chance superposition. On the other hand, the probability of a chance spatial superposition is about 1%, and the probability that the velocity would be so close to the systemic velocity is about 0.2, for a joint probability of about \( 2 \times 10^{-3} \).

The situation with Leo I is similar but less extreme. The right hand panel of Figure 3 shows that \( \text{H} \text{I} \) at the velocity of the galaxy is closely associated with it, even though no \( \text{H} \text{I} \) is detected toward the stars themselves. Nevertheless, the velocity centroid of the emission shown in the right hand panel of Figure 3 differs from the systemic velocity of the galaxy by about 30 km s\(^{-1}\). In this case, however, the gas shown in both panels is part of the same velocity component. While the extended emission shown in Figure 3 is unlikely to be
gravitationally bound to Leo I, it is more difficult to argue that this gas is also a chance superposition, not only because the lower velocity gas is part of the same velocity component, but also because the joint probability of having two galaxies in this small sample with two HI clouds in the same line of sight at velocities close to the systemic velocity is $< 10^{-5}$.

We note, however, that both galaxies are close to the 250 kpc boundary shown in Figure 4. Leo I is 250 kpc from the Milky Way (Mateo 1998) and LGS 3 is 270 kpc from the center of M31. Could it be that the HI seen in Figure 1 for each galaxy is beginning to be stripped by the ram-pressure of the hot halo gas? Certainly for LGS 3, the gas in Figure 1 looks as if it has been swept away from the galaxy itself. Tidal stripping is not an option for either galaxy because there is a systematic offset in velocity in only one sense; tidal stripping would produce plumes with velocities both larger and smaller than the systemic velocity of the dSph. From Equation 5, we find that the mean acceleration of the gas due to tidal stripping is $\sim 1.3 \times 10^{-10} \text{ cm s}^{-2}$. Gas is detected as much as 1°5 from LGS 3, or about 20 kpc in projection from the galaxy. With a velocity difference of 50 km s$^{-1}$, gas farthest from the galaxy will have taken $4 \times 10^8$ yr to reach that distance. Assuming that the acceleration is constant, ram-pressure stripped gas would attain a velocity of $\sim 15$ km s$^{-1}$ in that time. This is a bit on the low side, but the agreement is not unreasonable, given the uncertainty with which the critical parameters are known. The density of the hot gas might be somewhat higher, as might the velocity of the galaxy with respect to the hot halo gas, and projection effects can be important at the 50% level.

If the position and velocity offsets of the HI from LGS 3 are due to ram-pressure stripping, one would expect there to be a velocity gradient in the sense that the most extreme differences in velocity are seen farthest from the galaxy. The individual HI spectra that compose Figure 1 do not, however, show any detectable gradient in the extended cloud.

Ram-pressure stripping should produce velocity differences from the systemic velocity with well-determined signs: the velocity of the stripped gas should always be closer to the systemic velocity of either the MW or M31 than that of the dwarf being stripped. In the case of Leo I, the galaxy has a GSR velocity of $+178$ km s$^{-1}$; the anomalous velocity gas has a GSR velocity of $+158$ km s$^{-1}$, in accord with expectations. For LGS 3, the velocity relative to the GSR is about 25 km s$^{-1}$ more negative than that of M31, suggesting that the stripped gas should have a more positive velocity. But this is not the case; the stripped gas is 50 km s$^{-1}$ more negative. This discrepancy is difficult to reconcile with ram-pressure stripping.

We conclude that ram-pressure stripping can plausibly produce the magnitude of the velocity and positional offsets for LGS 3 and Leo I if the velocity of the galaxy relative to the hot gas and the density of the hot gas are within factors of two and three respectively
of the values assumed for them. The sign of the velocity offset for LGS 3, however, seems inconsistent with ram-pressure stripping.

4.4. Comparison of Dwarf Galaxy Envelopes with HVC Properties

In their paper on HVCs, Blitz et al. (1999) derived properties of HVCs under the assumption that they are typically at a distance of 1 Mpc; however they did not correct for beam smearing, which would lower both the diameters and the derived masses. Furthermore, if the typical HVC has a distance more like that of M31 than the 1 Mpc assumed, their derived masses may be too high by as much as a factor of 4, and their diameters too high by a factor of 2. A complete northern hemisphere HVC catalogue by Robishaw & Blitz (in preparation) will correct for beam smearing. Given this range of uncertainty, typical HVC H\textsuperscript{i} masses are about $5 - 20 \times 10^6 \, M_\odot$ if the HVCs are extragalactic and typical diameters are about 15 - 28 kpc. Some of the dwarf galaxy H\textsuperscript{i} envelopes are just in this range, notably DDO 210, Leo I, LGS 3, IC 10, Leo A, Sextans A, and possibly And V. Several others are confused with the velocities from Galactic foreground emission, and although their masses are in the correct range, the full extent of their H\textsuperscript{i} emission is poorly determined. Thus, numerous Local Group dwarfs have H\textsuperscript{i} properties virtually indistinguishable from extragalactic HVCs, and as pointed out in §4, two previously catalogued HVCs are apparently associated with galaxies.

This suggests that some of the HVCs might harbor undetected low surface brightness (LSB) galaxies, and searches are currently underway to detect galaxies toward the HVCs. If successful, this would bridge the gap between the non-detections of HVC analogues without stars in deep extragalactic H\textsuperscript{i} searches (Zwaan et al. 1997; Spitzak & Schneider 1998). On the other hand, the extragalactic H\textsuperscript{i} searches have sensitivities that trail off just at or above the derived typical HVC mass, especially if the masses derived by Robishaw & Blitz (in preparation) turn out to be lower, as expected. So there may nevertheless be a substantial population of low-mass intergalactic H\textsuperscript{i} clouds without associated stars. In either case, the HVCs might then turn out to be the missing dwarf galaxies in the simulations of Klypin et al. (1999).

4.5. Implications for Galaxy Formation and Evolution

Mateo (1998), Grebel (1999) and van den Bergh (1999b) discuss several problems associated with the apparent lack of interstellar gas in the dSph galaxies, most notably,
their complex star formation histories. Some galaxies seem to have had several episodes of star formation, including some as recently as 1–2 Gyr ago (Grebel 1999), but this hardly seems possible without at least some traces of gas that could have fueled this activity. The H\textsc{i} observations presented in this paper suggest that one way around this problem is that all of the Local Group dwarf galaxies have had loosely bound H\textsc{i} envelopes such as those seen for the galaxies at distances beyond the 250 kpc cutoff radius when the last episode of star formation took place. This loosely bound gas would be subject to small relatively localized perturbations that could lead either to star formation or gas disruption and may be why the star formation histories of the Local Group dwarfs are so heterogeneous (Mateo 1998; Grebel 1999). Dissipation in the gas might have generated both low levels of ongoing star formation as well as occasional large bursts until the orbits of the galaxies brought them within the hot halos around the MW and M31. Star formation would then have ended for the galaxies with H\textsc{i} column densities insufficient to withstand the ram-pressure stripping. Clearly, the extended H\textsc{i} envelope around Leo I is plausibly the source of the relatively recent star formation activity in that galaxy (e.g. Grebel 1998).

It is perhaps only when the galaxies venture within a radius of 250 kpc that the dwarfs become stripped of their H\textsc{i}, eventually losing their ability to form stars. The dynamical simulations of HVCs in the context of the evolution of the Local Group (Blitz et al. 1999) suggest that at least some of the dwarf galaxies inside the 250 kpc cutoff may be approaching the MW and M31 for the first time. To traverse the entire length of the hot halo for galaxies at a velocity of 60 km s\(^{-1}\) appropriate for the Local Group dwarfs (van den Bergh 1999a) takes \(8 \times 10^9\) yr, a substantial fraction of a Hubble time. Thus some of the dwarfs such as Carina may only recently have lost their gas, while others such as Ursa Minor, that show no evidence of recent star formation activity, may have orbits that kept them within the cutoff distance for most of a Hubble time.

If the connection between LSB dSph galaxies and the HVCs can be confirmed, it might also solve the metallicity problem for HVCs. That is, if the HVCs are extragalactic, they must have existed for a Hubble time, but the abundances and metallicities, while low, are not primordial (Wakker & van Woerden 1997; Wakker et al. 1999). How then did these HVCs get their metals? If the HVCs are associated with low levels of star formation as in the dSph galaxies, then the stars themselves could have contaminated the gas. With a range of \([\text{Fe/H}] \simeq -1\) to -2 dex for the stars in dwarf galaxies, one expects the gas to reflect these values. The best determined metallicity toward an HVC (complex C) is the measurement of S/H = 0.09 times the solar value (Wakker et al. 1999), as expected, but more measurements are needed.
5. Summary

We have shown that there is good evidence that nearly half of the dwarf spheroidal galaxies in the Local Group contain large quantities of gas in an extended distribution around each galaxy. Even without measured velocities for most of the galaxies, the associations of the gas with the galaxies must be real because the number of positional coincidences is more than two orders of magnitude greater than would be expected from random placements of both the galaxies and the HVCs. The properties of the HI associated with many of the dwarfs are similar to those expected for extragalactic HVCs, suggesting that the HVCs may harbor LSB galaxies similar to the dwarf galaxies in the Local Group.

We have investigated the reason for the great diversity in the neutral gas content of Local Group dwarf galaxies, and have shown that within 250 kpc of the center of both the MW and M31, the gas content drops precipitously. Both tidal and ram-pressure stripping can play a role in removing the gas, but ram-pressure stripping is more effective and can strip a galaxy completely. The inferred mean density of hot gas is \( \sim 2.5 \times 10^{-5} \text{ cm}^{-3} \).

Two of the Local Group dwarfs, LGS 3 and Leo I, have HI envelopes that differ from the systemic velocities by 50 km s\(^{-1}\) and 30 km s\(^{-1}\) respectively. The joint probability that both galaxies have unrelated clouds along the line of sight is \( \lesssim 10^{-5} \). Ram-pressure stripping could cause large velocity offsets, and in the case of Leo I, the inferred hot halo properties are in reasonable quantitative agreement with what is observed. For LGS 3, the agreement is less good, but may still be within the range of acceptability.

We find that the HI observations can explain qualitatively the diversity in the star formation histories of the Local Group dwarfs, both the presence and absence of recent star formation in individual dSphs.

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REFERENCES

Armandroff, T.E., Jacoby, G.H., & Davies, J.E. 1999, AJ, 118, 1220
Armandroff, T.E., Davies, J.E., & Jacoby, G.H. 1998, AJ, 116, 2287
Banks, G.D., et al. 1999, ApJ, 524, 612
Blitz, L., Spergel, D.N., Teuben, P.J., Hartmann, D., & Burton, W.B. 1999, ApJ, 514, 818
Braun, R., & Burton, W.B., 1999, A&A, 341, 437
Carignan, C. 1999, PASA, 16, 18
Carignan, C., Beaulieu, S., Côté, S., Demers, S., & Mateo, M. 1998, AJ, 116, 1690
Carignan, C., Demers, S., & Côté, S. 1991, ApJ, 381, L13
Côté, P., Mateo, M., Olszewski, E.W., & Cook, K.H. 1999, ApJ, 526, 147
Côté, P., Mateo, M., & Sargent, W.L.W. 2000, in preparation.
Einasto, J., Saar, E., Kaasik, A., & Chernin, A.D. 1974, Nature, 252, 111
Fouquée, P., Durand, N., Bottinelli, L., Gouguenheim, L., & Paturel, G. 1990, A&AS, 86, 473
Gallart, C., Martínez-Delgado, D., Aparicio, A., & Freedman, W.L. 1999, in The Stellar Content of Local Group Galaxies, Whitelock & Cannon, eds., ASP:San Francisco, p. 284
Grebel, E. 1999, in The Stellar Content of Local Group Galaxies, Whitelock & Cannon, eds., ASP:San Francisco, p. 17
Gunn, J.E., & Gott, J.R. 1972, ApJ, 176, 1
Hartmann, D., & Burton, W.B. 1997, Atlas of Galactic Neutral Hydrogen (Cambridge University Press:Cambridge) (LDS)
Hulsbosch, A.N.M., & Wakker B.P. 1988, A&AS, 75, 191
Karachentsev, I.D., & Karachentseva, V.E. 1999, a341, 355
Klypin, A.A., Kravtsov, A.V., & Valenzuela, O. 1999, ApJ, in press
Knapp, G.R., Kerr, F.J., & Bowers, P.F. 1978, AJ, 83, 360
Lin, D.N.C., & Faber, S.M. 1983, ApJ, 266, L21
Lo, K.Y., Sargent, W.L.W., & Young, K. 1993, AJ, 106, 507
Mateo, M. 1998, ARAA, 36, 435
McKee, C.F., & Hollenbach, D.J. 1980, ARAA, 18, 219
Moore, B., & Davis, M. 1994, MNRAS, 270, 209
Oosterloo, T., Da Costa, G.S., & Stavely-Smith, L., 1996, AJ, 112, 1969
Sembach, K.R., Savage, B.D., Lu, L., & Murphy, E.M. 1999, ApJ, 515, 108
Spitzak J.G., & Schneider, S.E. 1998, ApJS, 119, 159
St-Germain, J., Carignan, C., Côté, S., & Oosterloo, T. 1999, AJ, 118, 1235
Thuan, T.X., and Martin, G.E. 1979, ApJ, 232, L11
van den Bergh, S. 1999a, in The Stellar Content of Local Group Galaxies, Whitelock &
Cannon, eds., ASP:San Francisco, p. 3
van den Bergh, S. 1999b, A&A Reviews, 9, 273
Wakker, B.P., & van Woerden, H. 1991, A&A, 250, 509
Wakker, B.P., & van Woerden, H. 1997, ARAA, 35, 217
Wakker, B.P., et al. 1999, Nature, 402, 388
Weiner, B., Vogel, S., & Weymann, R. 2000, ApJ, in preparation.
Whiting, A.B., Irwin, M.J., & Hau, G.K.T. 1997, AJ, 114, 996
Young, L.M., & Lo, K. Y. 1997, ApJ, 490, 710
Young, L.M. 1999, AJ, 117, 1758
Zwaan, M., Briggs, F.H., & Sprayberry, D. 1997, ApJ, 490, 173