WHERE ARE THE HIGH-VELOCITY CLOUDS IN LOCAL GROUP ANALOGS?

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ABSTRACT

High-velocity clouds (HVCs) are clouds of H I seen around the Milky Way with velocities inconsistent with Galactic rotation; they have unknown distances and masses and controversial origins. One possibility is that HVCs are associated with the small dark matter halos seen in models of galaxy formation and distributed at distances of 150 kpc to 1 Mpc. We report on our attempts to detect the analogs to such putative extragalactic clouds in three groups of galaxies similar to our own Local Group using the Australia Telescope National Facility Parkes Telescope and Compact Array. Eleven dwarf galaxies were found, but no H I clouds lacking stars were detected. Using the population of compact HVCs around the Milky Way as a template, we find that our nondetection of analogs implies that they must be clustered within 160 kpc of the Milky Way (and other galaxies) with an average H I mass $\lesssim 4 \times 10^5 \, M_{\odot}$ at the 95% confidence level. This is in accordance with recent limits derived by other authors. If our groups are true analogs to the Local Group, then this makes the original Blitz et al. and Braun & Burton picture of HVCs residing out to 1 Mpc from the Milky Way extremely unlikely. The total H I mass in HVCs, $\lesssim 10^8 \, M_{\odot}$, implies that there is not a large reservoir of neutral hydrogen waiting to be accreted onto the Milky Way. Any substantial reservoir of baryonic matter must be mostly ionized or condensed enough as to be undetectable.

Subject headings: galaxies: formation — intergalactic medium — Local Group

1. INTRODUCTION

Forty years after first being discovered (Muller et al. 1963), the "high-velocity clouds" (HVCs) remain a mystery. HVCs are clouds of neutral hydrogen (H I) covering a large fraction of the entire sky with velocities inconsistent with simple Galactic rotation and in excess of ± 90 km s^{-1} of the local standard of rest (see Wakker & van Woerden 1997 for a review). In addition, they lack stellar emission (e.g., Simon & Blitz 2002). These facts make the determination of distances an intractable problem; without distances we are unable to determine their masses and discriminate between mechanisms responsible for their origins.

HVCs most likely represent a variety of phenomena. Some HVCs are probably related to a galactic fountain (Shapiro & Field 1976; Bregman 1980) and are located in the lower Galactic halo. Other HVCs are certainly tidal in origin: the Magellanic Stream is the most obvious of these features, formed via the tidal interactions among the Milky Way, Large Magellanic Cloud, and Small Magellanic Cloud (e.g., Putman et al. 1998), with other HVCs potentially related to the Sagittarius dwarf (Putman et al. 2004). Some HVCs may even be satellites unto themselves (e.g., Lockman 2003). Oort (1966, 1970) originally proposed that HVCs may be infalling primordial gas; Complex C may be such an example (Wakker et al. 1999; Tripp et al. 2003; cf. Gibson et al. 2001). Verschuur (1969) was the first to associate HVCs with the Local Group, with the idea resurrected by Blitz et al. (1999) for all HVCs and by Braun & Burton (1999) for the subset of compact HVCs (CHVCs).

These authors suggested that HVCs contained dark matter and could be related to the small dark matter halos predicted to exist in large numbers by cold dark matter models of galaxy formation (e.g., Klypin et al. 1999; Moore et al. 1999). In this scenario, Blitz et al. and Braun & Burton hypothesize that HVCs have $D \sim 1$ Mpc, and $M_{\rm H\,I} \sim 10^7 \, M_{\odot}$. Since these papers, much of the observational effort has focused on testing the association of CHVCs with dark matter halos and the formation of the Local Group. In addition, distance and mass estimates have decreased; de Heij et al. (2002b) suggested that the CHVC distribution has a Gaussian distribution about the Milky Way and M31 with $D \sim 150$–200 kpc and $M_{\rm H\,I} \sim 10^{5.5}$–$10^7 \, M_{\odot}$ but are still associated with dark matter halos.

If the Blitz et al. (1999), Braun & Burton (1999), and de Heij et al. (2002b) hypothesis is correct, then analogs to HVCs should be ubiquitous in other galaxy groups. Numerous attempts to find extragalactic analogs to HVCs have been initiated, but to date there have been no discoveries. A few authors have reported high-velocity gas around individual galaxies, but these HVCs are probably associated either with vigorous star formation (e.g., Schulman et al. 1994; Kamphuis & Sancisi 1993) or with tidal interactions (e.g., Kamphuis & Briggs 1992). Pisano et al. (2002) searched for H I clouds around 41 isolated quiescent galaxies. While they discovered 13 companions, all were dwarf galaxies. These studies all assumed that HVCs were associated with individual galaxies, while they may instead be unique to the group environment.

Lo & Sargent (1979) conducted one of the earliest searches for intergalactic H I in three loose groups. They detected four dwarf galaxies but lacked the sensitivity to detect HVC analogs. Over the typical FWHM of a CHVC (~ 30 km s^{-1}) their 5 σ sensitivity was 4×10^7 to $5 \times 10^8 \, M_{\odot}$. A more recent survey of one of the same groups, Canes Venatici I, by Kraan-Korteweg et al. (1999) had a detection limit of $\sim 10^8 \, M_{\odot}$ and also failed to find anything more than typical dwarf galaxies. Other studies of groups, such as those by Zwaan & Briggs (2000), Zwaan (2001), and de Blok et al. (2002), only probed a small fraction of their total area, reducing the probability of

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detecting analogs. In addition, these surveys did not explore spiral-rich groups akin to the Local Group. The most sensitive group survey to date is the Parkes HIDEEP survey (Minchin et al. 2003), which covered part of the Cen A group. Despite their 5 σ $M_{\rm H\,I}$ detection limit of 2×10^6 $M_\odot$ over 30 km s^{-1} at the distance of Cen A ($= 3.5$ Mpc; Cotê et al. 1997), Minchin et al. found no sources without optical counterparts, i.e., no HVC analogs.

Despite the large number of searches for HVCs, all these studies have crucial limitations. Some lack the sensitivity to detect HVC analogs, and others only surveyed a small region of the group reducing the number of expected detections. Perhaps most critically, however, is the lack of observations of groups similar to the Local Group. The Cen A group, for example, is a fairly dense group centered around a large elliptical galaxy, quite unlike the Local Group. If HVCs are unique to the relatively tame environment of the Local Group, then we may not expect to see them in the Cen A group or groups like it.

In this Letter, we present our observations of three loose groups of galaxies analogous to the Local Group with the Parkes multibeam and Australia Telescope Compact Array (ATCA)[6] and discuss the implications for the location of HVCs around the Milky Way. In § 2 we discuss the group properties and our observations. In § 3, we describe a model for the distribution of HVCs in the Local Group and its predictions for what we should see in our sample of groups. Finally, we conclude in § 4 by comparing our observations with the model prediction and discussing what this implies for HVCs in the Local Group.

2. OBSERVATIONS

We chose to observe three loose groups of galaxies that were qualitatively similar to the Local Group: LGG 93, LGG 180, and LGG 478 (Garcia 1993). These groups were selected to contain only large spiral galaxies that were typically separated by $\gtrsim 100$ kpc and spread over a diameter of ~1 Mpc. All of the groups are nearby, between 10.6 and 13.4 Mpc. At this distance, the Parkes beam of 14$'$.4 corresponds to a linear size of ~45 kpc. Between 2001 October and 2002 August, we observed an area of ~1 Mpc^2 $\equiv$ 25 deg^2 over a velocity range of greater than 1500 km s^{-1} centered on each group by scanning the multibeam receiver on the Parkes Telescope down to an rms sensitivity of 6–9 mJy beam^{-1} per channel. This translates to an rms mass sensitivity of $\lesssim 10^6$ $M_\odot$ per 3.3 km s^{-1}. Fake sources were inserted into the cubes, and multiple double-blind searches for all real and fake sources were conducted. All sources, not just new ones, identified by more than one search were confirmed with follow-up observations using the ATCA. On the basis of our identification of the fake sources, we determined that we detected all sources that had an integrated flux greater than 10 times the rms noise times the square root of the number of channels. This means that over a velocity width of ~35 km s^{-1} (the average FWHM velocity width of CHVCs), we can only detect sources in our Parkes and ATCA data with $M_{\rm H\,I} \gtrsim 10^7$ $M_\odot$. More detail on the groups, observations, reductions, and analysis will be presented in D. J. Pisano et al. (2004, in preparation). The properties of the groups and the observations are listed in Table 1.

In the three groups, all the known members were detected and eight new H I–rich dwarf galaxies were found with optical

TABLE 1
SAMPLE PROPERTIES

Group	Galaxies[a]	Velocity[b] (km s^{-1})	Distance[c] (Mpc)	Sensitivity[d] ($M_\odot$)
LGG 93	5 S	750	11.5	8×10^5
LGG 180	3 S, 6 Irr	725	11.1	6×10^5
LGG 478	3 S, 1 Irr	692	10.6	5×10^5

[a] The morphological types of group galaxies: S = spiral, Irr = irregular.
[b] The recession velocity of the group corrected for Virgocentric infall from Garcia (1993).
[c] The distance to the group calculated from the corrected velocity and assuming $H_0 = 65$ km s^{-1} Mpc^{-1}.
[d] The 1 σ mass sensitivity in one 3.3 km s^{-1} channel.

counterparts visible on the Digital Sky Survey or cataloged in the NASA/IPAC Extragalactic Database; no H I clouds without stars were discovered. In other words, no HVC analogs were found with $M_{\rm H\,I} \gtrsim 10^7$ $M_\odot$. At the distance of these groups, the Parkes beam is 45–55 kpc, but since our higher spatial resolution ATCA observations have the same sensitivity as the Parkes data we should detect any massive HVC analog that is more than ~5 kpc from a galaxy.

3. A MODEL FOR CHVCs

Because we did not detect any HVC analogs in the three groups surveyed, we are unable to directly measure the masses and spatial distributions of such clouds. Since these three groups are similar to the Local Group in terms of their morphology and the H I and halo mass functions (D. J. Pisano et al. 2004, in preparation), we can use our nondetections to infer the distribution of HVCs within the Local Group. To this end, we have constructed a simple model for the distribution of CHVCs around the Milky Way and other galaxies. Because CHVCs are the most likely class of HVCs to be dark matter–dominated and reside at larger distances from the Milky Way, we only consider this class of objects (Braun & Burton 2001).

For our model, we start with the cataloged CHVCs from Putman et al. (2002) and de Heij et al. (2002a) from the southern HIPASS and northern Leiden-Dwingeloo surveys. This yields 270 CHVCs with measured fluxes and velocity widths. We assume that these clouds are distributed with a three-dimensional Gaussian distance distribution around the Milky Way characterized by a given $D_{\rm HWHM}$. After assigning a distance to a cloud, we get an H I mass that we compare to our 10 σ detection limit for the cloud's velocity width to determine if we could detect this cloud in one of our groups. We carry out a Monte Carlo simulation with 10,000 trials noting the number of times that we have zero detections. We do this for a variety of $D_{\rm HWHM}$ values, ranging from 50 to 500 kpc, and for differing parent numbers of CHVCs, ranging from 27 to 1728 clouds (0.1–6.4 times the number of Galactic CHVCs). Two examples of this model are presented in Figure 1 for a total number of 270 CHVCs with $D_{\rm HWHM} = 500$ kpc (*left*) and 250 kpc (*right*). Note that for the latter model, distinctly fewer CHVCs would have been detected in our survey. While our model is distinctly less complex than those of previous authors (e.g., Blitz et al. 1999; Braun & Burton 1999; de Heij et al. 2002b) that include assumptions as to the physical properties of HVCs, it can be seen as a generalization of these models. For reference, the Blitz et al. (1999) and Braun & Burton (1999) models have $D_{\rm HWHM} = 500$ kpc, while the de Heij et al. (2002b) model has $D_{\rm HWHM} = 150$ kpc.

There are a few important aspects of this model that may limit
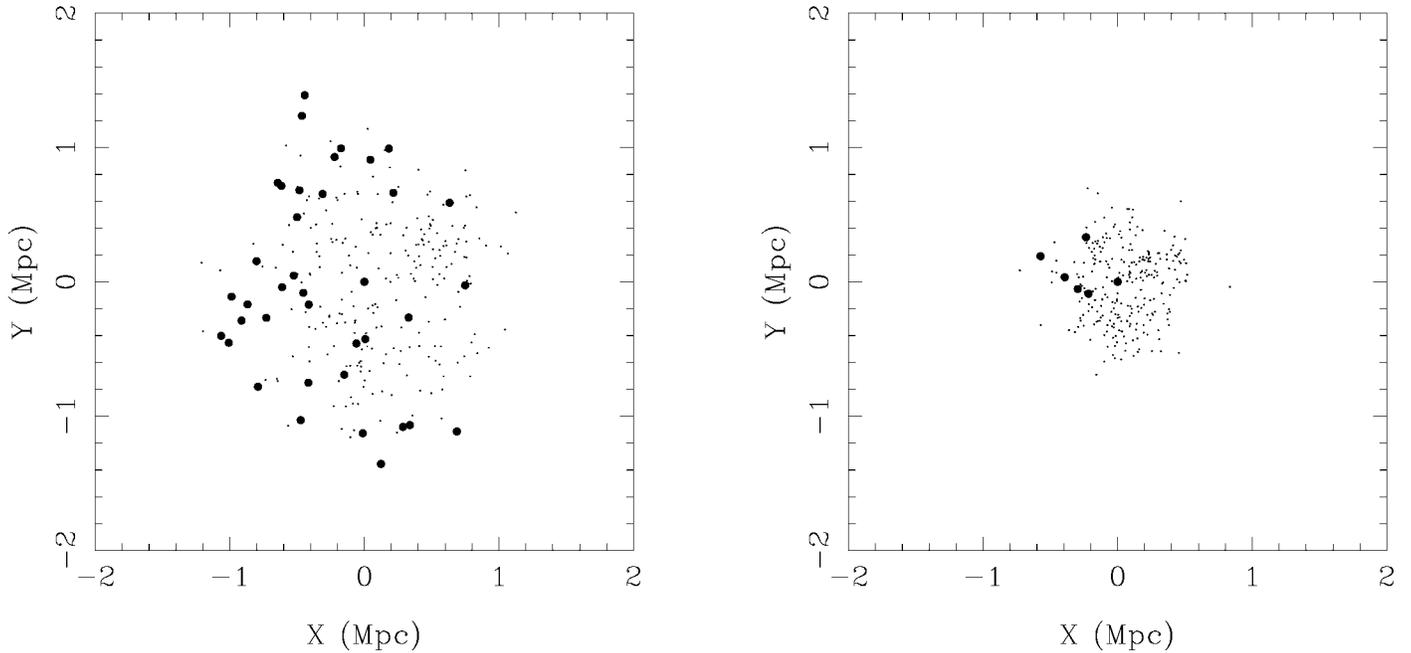
FIG. 1.—*Left*: Simulation of all 270 cataloged CHVCs from Putman et al. (2002) and de Heij et al. (2002a) around the Milky Way (*large filled circle in center*) distributed with a random three-dimensional Gaussian distance distribution with $D_{\mathrm{HWHM}} = 500$ kpc. Filled circles would be detected by our survey; dots would not if the Milky Way were at the distance of our groups. *Right*: Same as left, but for $D_{\mathrm{HWHM}} = 250$ kpc. Note that there are many fewer expected detections.

its potential utility. First of all, as can be seen in Figure 1, we do not expect to detect the vast majority of CHVCs at the distance of our groups but only the most massive. As D_{HWHM} decreases, this becomes more of an issue. For example, at $D_{\mathrm{HWHM}} = 500$ kpc, the average CHVC H I mass is $\sim 10^7\ M_\odot$, while our detection limit is over $10^7\ M_\odot$, but at $D_{\mathrm{HWHM}} = 250$ kpc, the average H I mass is only $\sim 10^6\ M_\odot$. As such, the detailed nature of the flux and line width distributions of CHVCs around the Milky Way is of critical importance. If this is different around other galaxies in other groups, in particular if the highest flux CHVCs are absent in such groups, then this model may not yield accurate limits.

It is also important to note that the number of CHVCs ob-

served around the Milky Way may not be equal to the total number present, neither of which needs to be equal to the number around galaxies in other groups. This is why we vary the total number of CHVCs in our model. If the number is higher, then the constraints will be stronger. If other types of HVCs are considered or the existing catalogs of CHVCs are incomplete, then again we would expect to detect more analogs so our distance constraints would be more stringent. We can, however, make a rough estimate of how many clouds we expect in each group. Cold dark matter simulations of the formation of the Local Group (Klypin et al. 1999) show that the number of satellites per galaxy is proportional to the mass of that galaxy, which is proportional to the cube of that galaxy's circular velocity, $N_{\mathrm{CHVC}} \propto M_{\mathrm{galaxy}} \propto V_{\mathrm{circ}}^3$. This can also be argued via the Tully-Fisher relation (Tully & Fisher 1977). Using published inclinations and measured velocity widths for each group galaxy the number of expected CHVCs in each group is within a factor of 2 of the number seen around the Milky Way. This is accounted for in our model comparisons but will not have a major effect on our distance limits. Finally, it is possible that HVCs are present in all of the groups that we observed but that they effectively cover the entire area of the group. In this case, in our reductions we would have subtracted out the real signal as sky. This is unlikely as Milky Way HVCs only cover 37% of the sky down to a column density of $7 \times 10^{17}\ \mathrm{cm}^{-2}$ (Murphy et al. 1995). Furthermore, such a distribution would be inconsistent with the statistics of Mg II and Lyman limit absorption-line systems seen toward quasars (Charlton et al. 2000).
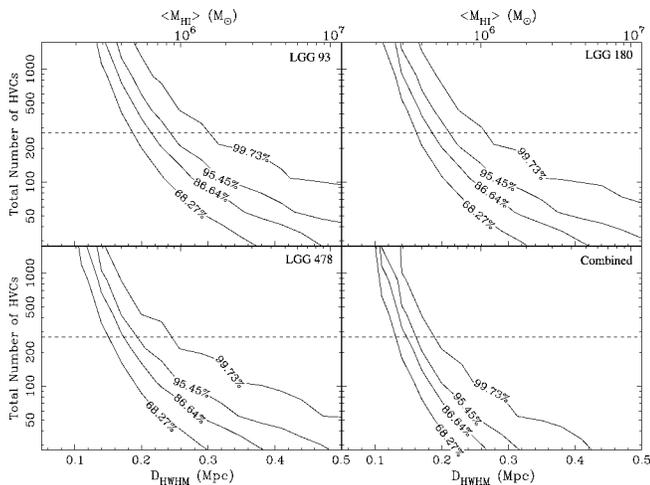
4. WHERE ARE THE CHVCs?

Figure 2 shows the probability of zero detections as a function of the parent number of CHVCs, D_{HWHM}, and the average $M_{\mathrm{H\,I}}$ of CHVCs for each group and the combined probability for the three groups. We can combine the individual group probabilities since

FIG. 2.—Plot of the probability of zero detections as a function of the number of CHVCs per group and D_{HWHM} (or the average H I mass of the CHVC) for the distribution of Milky Way CHVCs for each group and the combined probability for all three groups as labeled on the panels. The dashed line marks the number of CHVCs identified around the Milky Way.

they are independent experiments. The figure shows that our non-detection of HVC analogs means that the average H I mass of CHVCs must be less than $10^6\,M_\odot$ at the 95.45% confidence level. This assumes that the properties of CHVCs in these groups are the same as those cataloged in the Local Group. If this is the case, then we can infer that for this H I mass, CHVCs in the Local Group must be clustered within $D_{HWHM} < 160$ kpc of the Milky Way. If we were to consider all HVCs in our model, then these limits would be even stronger. This conclusion is robust even when considering different models for the CHVC distribution. The average H I mass of CHVCs is the same if they are distributed in a filamentary manner or if we adopt the de Heij et al. (2002b) model. These limits are inconsistent with the original models of Blitz et al. (1999) and Braun & Burton (1999), which would have median distances of ~1 Mpc with an $M_{H I}$ of ~$10^7\,M_\odot$. Our sensitivity is not sufficient to constrain the best-fit de Heij et al. (2002b) model.

Our results, when compared with those of other authors, reveal a remarkably consistent picture for the distribution of HVCs in close proximity to individual galaxies. Zwaan's (2001) study of parts of five groups with Arecibo constrained HVCs to be within 200 kpc of group barycenters. Braun & Thilker (2004) and Thilker et al. (2004) report on a possible population of HVCs around M31 with $M_{H I}$ ranging from 10^5 to $10^7\,M_\odot$ and a Gaussian distance dispersion of 55 kpc. Attempts to measure or model the distances to HVCs observed around the Milky Way also point to this same picture. The few direct stellar absorption-line distances available for HVC complexes place these clouds within ~10 kpc of the Milky Way (Wakker 2001). Putman et al.'s (2003) Hα observations of HVCs and CHVCs around the Milky Way constrain those clouds to be within ~40 kpc of the Galaxy, assuming a model for the escaping ionizing radiation. Maloney & Putman (2003) and Sternberg et al. (2002) modeled CHVCs as gaseous objects within dark matter halos while accounting for the effects of ionization, thermal balance, and confinement by an external medium and determined that CHVCs must lie within 150 kpc of the Milky Way. Finally, de Heij et al.'s (2002b) model of the Local Group distribution of CHVCs using their assumed physical properties predicts a distribution with $D_{HWHM} \sim 150$–200 kpc.

At these distances CHVCs are more closely associated with the Milky Way than the Local Group, which suggests that these clouds are associated more with individual galaxy formation instead of group formation, as originally suggested by Blitz et al. (1999). Also at these distances, the total H I mass in CHVCs is $\lesssim 10^8\,M_\odot$ and even with substantial dark matter would only contribute a small fraction of the total mass of the Local Group. They would still contribute fuel for star formation in the Milky Way but only as much H I as a single dwarf galaxy. On the other hand, CHVCs may still be the repository for large amounts of ionized gas (Maloney & Putman 2003; Sternberg et al. 2002), which could condense onto the Milky Way. Interestingly, the similarity of the inferred radial distribution of CHVCs with Milky Way satellites and models of galaxy formation (Kravstov et al. 2004) may actually strengthen the argument that CHVCs are associated with low-mass dark matter halos. Future searches for CHVC analogs associated with galaxy formation with properties such as those inferred by de Heij et al. (2002b) will be difficult because of their low masses. It will also be difficult to infer the origin of any such analogs. Within 160 kpc of a galaxy, H I associated with galactic fountains and tidal interactions will be prevalent, making the identification of CHVCs associated with galaxy formation difficult. Nevertheless, if we can find gas clouds associated with galaxy formation it will not only shed light on the nature of HVCs, but serve as a valuable check on models of galaxy formation.

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