Neutral Hydrogen and the Missing Satellites of the Local Group

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Abstract. We present a comparison of the leftover satellites at z=0 in a cold dark matter dominated simulation of the formation of the Local Group to the distribution of observed neutral hydrogen high-velocity clouds and compact high-velocity clouds. The ~2000 leftover satellites in the simulation have dark matter masses which range between 0.5 to \(10 \times 10^9\) M_☉, sizes between 3 to 30 kpc, and distances between 100 kpc and 2 Mpc. The dark matter halos show a clear bias in their distribution towards M31 and to a lesser extent towards the Local Group anti-barycenter. If the Local Group halos contain \(~1\%\) of their dark matter mass in neutral hydrogen they should have been easily detected by the current HI surveys. The only HI objects detected with the potential to be the Local Group halos are the high-velocity clouds. Here the spatial, kinematic, and HI flux properties of the clouds and dark matter halos are compared. Several different subsets of halos which may be more likely to contain neutral hydrogen are investigated, and the HVCs are found to have some similar properties to those halos within 500 kpc of the Galaxy and those halos with dark matter masses \(> 2 \times 10^8\) M_☉. The compact high-velocity clouds do not show similar properties to the halos.

1. Introduction

The distribution of neutral hydrogen in the universe is largely traced by the Lyα forest, Ly-limit systems, damped Lyα systems and galaxies, but the relationship between these tracers remains unknown. The predicted existence of a large number of individual dark matter halos in groups of galaxies by the cold dark matter (CDM) models of the formation of galaxies and clusters may provide a clue to the link between these features. If the excess satellites/halos exist, do they trace the HI distribution of the group and explain the abundance and location of the absorbers? All-sky HI surveys have detected only one type of object which could be the abundance of dark matter halos scattered throughout the Local Group. These are the high-velocity clouds (HVCs).

Using a standard CDM model of the formation of the Local Group (Moore et al. 2001), we compare the properties of the cold dark matter halos with those of the high-velocity clouds and compact high-velocity clouds (CHVCs) to
determine if these objects may solve the “missing satellite” problem. If the halos trace the H\textsubscript{I} distribution of a cluster, we are also able to place strong constraints on the fraction of neutral hydrogen associated with the dark matter.

2. Observations

The high-velocity cloud H\textsubscript{I} properties come from the $\sim 35'$ spatial resolution catalog of Wakker (priv comm). The Wakker catalog is adapted from the catalog of Wakker \& van Woerden (1991) and uses data from the Dwingeloo Telescope in the north (Hulsbosch \& Wakker 1988) and the IAR 30m in the south (Morras et al. 2000). This HVC catalog was used because it is from a fairly homogeneous resolution and sensitivity all-sky HVC dataset and uses a single catalog method. The data have a 5\(\sigma\) brightness temperature sensitivity of $\sim$0.05 K when it is smoothed kinematically. In this catalog of 626 clouds, the large complexes such as Complex C and the Magellanic Stream are classified as one object, leading to a distinct difference in the number of individual objects between this catalog and the southern HVC catalog of Putman et al. (2001). The Putman et al. catalog (described below) was designed to catalog smaller objects and only merges clouds if the brightest enclosing contour is $> 0.4$ T\textsubscript{max}. This catalog has 1956 clouds in it and the flux distribution has a significantly steeper slope. See Putman et al. for the distribution plots of this catalog.

We also investigated the properties of the compact high-velocity clouds (CHVCs). CHVCs were originally defined by Braun \& Burton (1999) as isolated clouds with diameters less than 2\(''\) (based on the 50\% of peak N\textsubscript{H\textsubscript{I}} contour). This definition was slightly revised in the higher resolution and sensitivity Putman et al. catalog of CHVCs to use the 25\% of the peak N\textsubscript{H\textsubscript{I}} contour. The HIPASS (HI Parkes All-Sky Survey; Barnes et al. 2001) data used in the Putman et al. catalog provide a marked improvement in the detectability of CHVCs, so this catalog has been combined with the predominantly northern catalog of Braun \& Burton, which was extracted primarily from the Leiden-Dwingeloo Survey (LDS) data (5\(\sigma\) $\approx$ 0.1K). The total number of CHVCs is 215. The Putman et al. catalog covers declinations less than $+2$\(\degree\) and uses HIPASS data reduced with the minmed5 method (Putman 2000). HIPASS has a spatial resolution of 15.5\(\prime\), a spectral resolution, after Hanning smoothing, of 26.4 km s\(^{-1}\), and a 5\(\sigma\) rms brightness temperature sensitivity of approximately 0.04 K, which corresponds to a 5\(\sigma\) column density sensitivity of $2.5 \times 10^{18}$ atoms cm\(^{-2}\) for an HVC with a linewidth of 35 km s\(^{-1}\). The HIPASS HVC data is complete to fluxes of 2–4 Jy km s\(^{-1}\), however the catalog may only be 100\% complete to total fluxes of 25 Jy km s\(^{-1}\) (see Putman et al. 2001).

The primary selection effect when cataloging HVCs and CHVCs is the gap in the velocity distribution due to the presence of Galactic H\textsubscript{I}. Clouds between $|v_{\text{LSR}}| = 90$ km s\(^{-1}\) are missing in all of the catalogs discussed above. This can be translated to a missing $v_{\text{LGSR}}$ population with the equation, $|v_{\text{LGSR}}| = v_{\text{LSR}} + 220\sin(\ell)\cos(b) - 62\cos(\ell)\cos(b) + 40\sin(\ell)\cos(b) - 35\sin(b)$ (Braun \& Burton 1999).
3. Simulation

We analyze a binary pair of massive halos that form in a hierarchical universe dominated by cold dark matter. The masses, separation and relative velocities of the binary halos are close to those observed for the Milky Way and Andromeda. The binary system was chosen from a large cosmological system such that a nearby massive cluster similar to Virgo was present. The simulation is described in detail in Moore et al. (2001). At \( z = 0 \), each halo contains \( \sim 2 \times 10^6 \) particles and is resolved to a distance of 0.1% of the virial radius, \( r_{200} \approx 200 \) kpc. The peak circular velocities of the halos are 220 km s\(^{-1}\) and 200 km s\(^{-1}\). These two halos are infalling for the first time at \( \approx 100 \) km s\(^{-1}\) and their outer edges are separated by 700 kpc. Over 2000 smaller dark matter halos lie within the high-resolution region and mostly within the virial radii of the two large halos that represent the Milky Way and Andromeda. It is these low mass dark matter halos that constitute the “missing satellite” problem for CDM models – the Local Group galaxies make up just 1-2% of the expected number of satellites.

4. Results

Figure 1 shows the spatial distributions of all of the Local Group dark matter halos, the high-velocity clouds (without distance constraints; see below), and the compact high-velocity clouds in Galactic coordinates. The dark matter halos show a clear bias in their distribution towards M31 and the Local Group anti-barycenter region. This bias in the distribution is independent of the size and mass of the halos, however, in terms of distance, it only appears beyond \( \sim 500 \) kpc of the Milky Way (see Figure 2). The distribution of cataloged HVCs shown in the middle panel of Figure 1, excludes those HVCs which have distance determinations. Direct distance determinations have been made to several of the larger high velocity complexes which place them within approximately 10 kpc of the Galaxy (e.g. Complex A, M, and WE; Wakker 2001), and the Stream and Leading Arm originated from the interaction of the Magellanic Clouds with the Milky Way and are at distances within 100 kpc. We can also exclude those complexes which are bright in H\( \alpha \) emission (e.g. Complex L, GCP (the Smith Cloud), and C), as this emission would not have been detected at distances greater than 100 kpc (e.g. Bland–Hawthorn & Maloney 1999), unless associated with an active star forming region. There are excesses of HVCs in the same general directions as the halos, but the extreme overabundance in the direction of M31 is not present. Furthermore, the distance determination methods have not uniformly sampled the sky, and this bias in the HVC distribution may disappear with future observations. The CHVCs shown in the bottom panel of Figure 1 are clustered, but clearly show a different distribution to the Local Group halos.

Figure 2 shows the spatial distributions of only those Local Group halos at least 300 kpc from both M31 and the Galaxy (top), within 500 kpc of the Galaxy (middle), and those halos with dark matter masses \( > 2 \times 10^8 \) M\(_{\odot}\). The bias in the spatial distribution of the halos is not evident within 500 kpc of the Galaxy. The beginning of an asymmetric distribution is seen between 500 and 800 kpc in this simulation. Since the simulation places the center of M31 at 1100 kpc, rather than the observed distance of 700 kpc (Freedman & Madore
Figure 1. The spatial distribution of all of the Local Group dark matter halos (top), high-velocity clouds (middle; excluding those clouds with distance constraints), and compact high-velocity clouds (bottom) in Galactic coordinates.
Figure 2. The spatial distribution of the Local Group halos more than 300 kpc away from the Galaxy and M31 (top), within 500 kpc of the Galaxy (middle), and those halos with dark matter masses greater than $2 \times 10^8 \, M_\odot$ (bottom) in Galactic coordinates.
Figure 3. The velocity distribution of the Local Group halos (top), HVCs (middle; excluding those clouds with distance constraints) and CHVCs (bottom) in terms of the Local Group Standard of Rest ($v_{LGSR}$).

Table 1. Cloud and Halo Properties

| Object                              | #  | Mean $v_{LGSR}$ |
|-------------------------------------|----|-----------------|
| HVCs (without distance constraints) | 469| -49             |
| CHVCs (Compact HVCs)               | 215| -57             |
| All dark matter halos              | 2135| -66             |
| Halos outside of 300 kpc           | 1530| -69             |
| Halos within 500 kpc               | 584 | -27             |
| Halos with $M_{DM} > 2 \times 10^8 \, M_\odot$ | 624 | -63             |
Figure 4. The velocity distribution ($l$ vs. $v_{\text{LSR}}$) of the Local Group halos beyond 300 kpc of both the Galaxy and M31 (top), at distances less than 500 kpc from the Galaxy (middle) and with dark matter masses greater than $2 \times 10^8 \, M_\odot$ (bottom).
1990), the actual bias in the distribution could appear somewhat closer. The asymmetric distribution of halos remains in both the $> 300$ kpc and $> 2 \times 10^8$ $M_\odot$ cases, but the total number of objects is greatly decreased (see Table 1).

The velocity distributions of all of the dark matter halos, HVCs without distance constraints, and CHVCs are shown in terms of Galactic longitude ($l$) and Local Group Standard of Rest velocity ($v_{\text{LGSR}}$) in Figure 3. Their mean LGSR velocities are tabulated in Table 1. There is no obvious position-velocity relationship between the populations of clouds and the Local Group halos. A wide range of velocities about M31 is shown in the simulation, as is a clear bias for negative $v_{\text{LGSR}}$s (i.e. infall). The HVC and CHVC velocity distributions are limited by confusion with Galactic emission between $v_{\text{LSR}} \approx +/− 90$ km s$^{-1}$. This is evident in the HVC distribution shown in the middle panel of Figure 3, with the HVCs clustering about a sinusoidal gap in the distribution. Both the HVCs and CHVCs show a preference for negative velocities in the Local Group reference frame. The CHVCs show a tendency towards more positive velocities at $l > 180^\circ$ and negative velocities at $l < 180^\circ$, with the largest range of velocities about $l = 0^\circ$. The panels of Fig. 4 show the velocity distributions of the selected groups of halos shown in Fig. 2. The velocity distribution of the Local Group halos within 500 kpc is fairly uniform, as is the spatial distribution, with a mean $v_{\text{LGSR}}$ the same magnitude more positive than the HVCs ($\sim 20$ km s$^{-1}$) as the other halo populations are more negative. The population of halos with $M_{\text{DM}} > 2 \times 10^8$ $M_\odot$ appears as a thinned version of the velocity distribution of all of the halos. Those halos over 300 kpc from M31 and the Galaxy have a similar thinned distribution, but there is less scatter and less extreme velocities in the direction of M31.

Though it is difficult to infer a mass distribution of the HVCs and CHVCs due to their unknown distances ($M_{\text{HI}} \propto D^2$), we can infer a HI flux distribution of the halos using their masses and distances and assuming a certain percentage of HI gas is associated with the dark matter. If the halos contain 1% of their dark matter mass in neutral hydrogen, their total HI fluxes are directly comparable to those of the HVCs and CHVCs, as shown in Figure 5. Note that some of the plots have different values on both axes. The projected HI flux distribution of all of the dark matter halos is shown in the bottom left panel of Figure 5 by the solid points. The slope is -1.5, which is the same as that of the HVCs shown in the upper left panel, but the number of halos in each flux bin is much higher. The upper right panel shows that both the total number of CHVCs and the slope of the HI flux distribution ($f(F_{\text{HI}}) \propto F_{\text{HI}}^{-1.8}$) is different from that of the halos. The selected populations of halos discussed above are shown in the bottom two panels of Figure 5. Halos outside of 300 kpc from the Galaxy and M31 are represented by the dashed line in the bottom left panel. The total number of clouds is again somewhat higher than that of the HVCs and the slope is steeper, like the CHVCs. The HI flux distribution of those halos within 500 kpc of the Galaxy ($f(F_{\text{HI}}) \propto F_{\text{HI}}^{-1.55}$; solid points in the bottom right panel) and those halos within 500 kpc of the Galaxy ($f(F_{\text{HI}}) \propto F_{\text{HI}}^{-1.6}$; dashed line in the bottom right panel) are the most comparable to the HVCs in terms of total number and slope. The size distribution of the halos is another property which can be compared to the HVCs if one assumes that the gas and dark matter are coupled. These plots will be shown in a future paper.
Figure 5. The HI flux distribution of the HVCs (upper left; $f(F_{HI}) \propto F_{HI}^{-1.5}$), CHVCs (upper right; $f(F_{HI}) \propto F_{HI}^{-1.8}$), and the Local Group halos if the halos currently contain 1% of their dark matter mass in neutral hydrogen. Note the different axes values on these plots. The bottom left panel shows all of the dark matter halos (solid points; $f(F_{HI}) \propto F_{HI}^{-1.5}$) and those halos outside of 300 kpc from both M31 and the Galaxy (dashed line; $f(F_{HI}) \propto F_{HI}^{-1.8}$). The bottom right panel shows those halos with masses less than $2 \times 10^8$ M$_\odot$ (solid points; $f(F_{HI}) \propto F_{HI}^{-1.5}$) and within 500 kpc of the Galaxy (dashed line; $f(F_{HI}) \propto F_{HI}^{-1.6}$). The data is binned in equal intervals of log($F_{HI}$) and the slopes are quoted in linear units.
Figure 5 also shows that even if the Local Group halos are not HVCs or CHVCs, they should have been detected by the recent large area HI surveys if they contain $\sim 1\%$ of their dark matter mass in neutral hydrogen. For instance, HIPASS covers over half of the sky and the velocities of the Local Group galaxies with a completeness level of $\sim 4$ Jy km s$^{-1}$, and the Wakker catalog reaches fluxes of $\sim 5$ Jy km s$^{-1}$ (Wakker & van Woerden 1991). Therefore, considering the entire population of halos (2135 total), almost all of them would have been detected if they contain 1% or greater of their dark matter mass in H I. By applying cuts in halo distance or mass, the number of halos which should have been detected is in closer agreement with the number of HVCs without lowering $M_{HI}$ to below 1% $M_{DM}$.

5. Discussion

There does not appear to be a close correlation between the entire population of dark matter halos in this standard cold dark matter Local Group simulation and the high-velocity clouds and compact high-velocity clouds. However, when cuts are made in distance or mass, the remaining halos show properties which could be argued are consistent with those of the HVCs without distance constraints. The compact HVCs do not show similar properties to the dark matter halos. The justification behind the halo cuts are summarized below. For greater than 300 kpc from M31 and the Galaxy, it is possible that the neutral hydrogen gas would not survive outside of a particular distance from these galaxies. This could be due to either ram pressure or tidal stripping effects (e.g. Quilis & Moore 2001), or ionizing radiation escaping from the galaxy (e.g. Bland-Hawthorn & Maloney 1999). The cut which requires the halos associated with neutral hydrogen gas be within 500 kpc, is based on the idea that the H I is only able to condense within a certain radius of the Galaxy (e.g. Oort 1970). Finally, the choice of only those halos with dark matter masses above $2 \times 10^8$ M$_\odot$ having neutral gas associated with them comes from CDM simulations which include reionization at $z \approx 6 - 10$ (e.g. Gnedin 2000). The increase in temperature of the gas during reionization suppresses the formation of low mass satellites due to a reduction in gas mass via the expulsion of already accreted gas and the suppression of further accretion. The primary difference between these sub-populations of halos and the entire population is a reduction in the total number, but there are also differences in the flux distributions and within 500 kpc there is certainly a more uniform spatial and kinematic distribution.

Considering the distance determinations which have been made to some of the larger high velocity complexes and the search for HVCs in other groups which have not found extragalactic HI clouds without stars down to $M_{HI}$ levels of $7 \times 10^6$ M$_\odot$ (e.g. Zwaan 2001), the possibility of the HVCs being the dark matter halos within a certain radius of the Milky Way seems the most likely possibility. If the nearby halos are represented by HVCs, are the further away halos represented by the lower column density Ly$\alpha$ absorbers which have been detected in other groups (e.g. Penton, Shull & Stocke 2000)? It is difficult to find these low column density systems within the Local Group due to the damping wings of the Galaxy’s Ly$\alpha$ and to some extent Ly$\beta$ absorption lines obscuring those velocities. The detection of these systems through other
absorption lines may be possible in some cases (e.g. \( N_{HI} > 10^{14} \)), and may have already been detected along some sightlines (e.g. Sembach et al. 1999). Evidence for a link between HVCs and these few absorption line detections of lower \( HI \) column density high velocity gas lies in their spatial and kinematic relationship. Therefore, if this gas is related to the \( Ly\alpha \) absorbers, one might expect to detect higher column density systems akin to HVCs in the vicinity of some of the low-redshift \( Ly\alpha \) absorber systems.

The \( HI \) flux distribution plots of the halos, presented in the bottom two panels of Figure 5, put strong constraints on the amount of neutral hydrogen the halos can have. HIPASS and other HVC surveys cover the velocities of all of the Local Group galaxies down to \( HI \) flux levels of 2-5 Jy km s\(^{-1}\). Figure 5 shows that the majority of the halos should have been detected if they contain at least 1% of their dark matter mass in \( HI \). Since only \( \sim 20 \) Local Group galaxies have been detected in \( HI \), there is an obvious need to look towards other objects. The number of HVCs and CHVCs is also too low to agree with the number of halos that should have been detected, unless one applies distance and/or mass cuts (see Figure 5 and Table 1). No other candidate “missing satellites” have been detected in \( HI \) in the Local Group, so either the HVCs are a population of the missing satellites, or the majority of the dark matter halos contain < 1% of their dark matter mass in \( HI \).

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