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What do loose groups tell us about galaxy formation?

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We present the results of a Parkes Multibeam HI survey of six loose groups of galaxies analogous to the Local Group. This survey was sensitive to HI-rich objects in these groups to below $10^7 M_\odot$ of HI, and was designed to search for low mass, gas-rich satellite galaxies and potential analogs to the high-velocity clouds seen around the Milky Way. This survey detected a total of 79 HI-rich objects associated with the six groups, half of which were new detections. While the survey identified a small number of dwarf galaxies, no star-free HI clouds were discovered. The HI mass function of the six groups appears to be roughly flat as is that of the Local Group. The cumulative velocity distribution function (CVDF) of the HI-rich halos in the six groups is identical to that of the Local Group. Both of these facts imply that these groups are true analogs to the Local Group and that the Local Group is not unique in its lack of low-mass dwarf galaxies as compared to the predictions of cold dark matter models of galaxy formation. This survey also constrains the distance to and HI masses of the compact high-velocity clouds (CHVCs) around the Milky Way. The lack of CHVC analog detections implies that they are distributed within $\lesssim$160 kpc of the Milky Way and have average HI masses of $\lesssim 4\times10^5 M_\odot$. The spatial distribution of CHVCs is consistent with the predictions of simulations for dark matter halos. Furthermore the CVDF of Local Group galaxies plus CHVCs matches the predicted CVDF of cold dark matter simulations of galaxy formation. This provides circumstantial evidence that CHVCs may be associated with low-mass dark matter halos.

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1. Introduction

Current models of hierarchical galaxy formation predict that galaxies form via the accretion of smaller lumps of gas, stars, and dark matter (e.g Kauffmann, White, & Guiderdoni, 1993). Simulations of this process assuming a cold dark matter (CDM) universe uniformly predict the existence of large numbers of low-mass dark matter halos surrounding massive galaxies today (e.g. Klypin et al., 1999; Moore et al., 1999). For the Local Group these authors have shown that the simulations predict an order of magnitude more dark satellites than known luminous galaxies; a discrepancy described as the "missing satellite" problem. Blitz et al. (1999) and Braun & Burton (1999) suggested that some or all of the "high-velocity clouds" (HVCs; see Wakker & van Woerden, 1997, for a review) may be associated with these dark matter halos and resolve this problem. Blitz et al. (1999) and Braun & Burton (1999) predicted that such HVCs would reside at distance of $\sim$1 Mpc and have $M_{HI}\sim 10^7 M_\odot$. More recently de Heij, Braun, & Burton (2002b) have predicted that only the compact HVCs (CHVCs) are associated with dark matter halos, and that they are closer (D$\sim$50-150 kpc) and less massive ($M_{HI}\sim 10^{5-7} M_\odot$) than the Blitz et al. (1999) and Braun & Burton (1999) predictions. An alternative possibility is that the Local Group is somehow unique in its deficit of low-mass galaxies. To test these hypotheses we have been conducting an HI survey of six spiral-rich loose groups analogous to the Local Group using the Parkes Multibeam instrument to search for low-mass, gas-rich dwarf galaxies and analogs to the Local Group HVCs. These observations will serve as a benchmark for the HI properties of galaxies within loose groups and a test of models of galaxy formation.

The sample selection, parameters of the survey, and the initial results from the first half of the survey are described in Pisano et al. (2004) and Pisano (2004), and will not be discussed here in great detail. This paper will focus on the initial analysis of the entire sample and the implications for the properties of loose groups, galaxy formation, and the nature of HVCs.

2. Group Properties

Our sample of six loose groups was chosen from Garcia (1993) to only contain spiral galaxies which were typically separated by $\sim$100 kpc and spread over an area of $\sim$1 Mpc^2. All six groups are located between 10-14 Mpc. Our Parkes Multibeam survey on the entirity of these groups was sensitive to objects with $M_{HI}\gtrsim 10^7 M_\odot$. We detected a total of 79 HI-rich objects in the six groups, half of which were previously unknown. All detections appear to have stellar counterparts. While we have chosen groups that are qualitatively similar to the Local Group, we wish to determine if they are quantitatively analogous as well. We will use two measures to do this. First, we will compare the shape of the composite HI mass function (HIMF) of the six groups with that of the Local Group. Second, we will compare the cumulative velocity distribution function (CVDF) of the Local Group and the loose groups.

Figure 1 shows the HIMF of the Local Group and the sum of the six loose groups we observed. The binned values simply represent the total number of galaxies in each bin and not the volume density of galaxies per dex. Our group survey begins to be incomplete for $M_{HI}<10^8 M_\odot$, which

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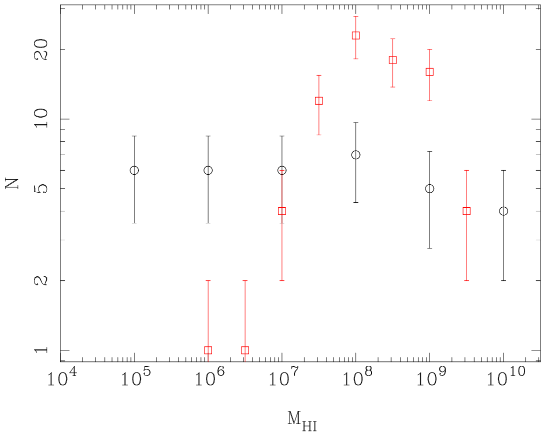

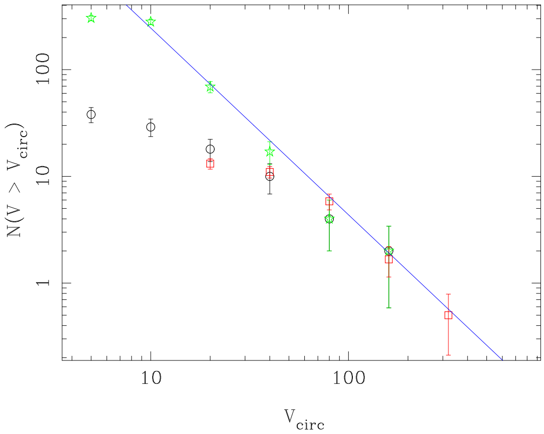

Figure 1: (Left) The HI mass function (HIMF) of the Local Group (black circles) and the sum of the six loose groups (red squares).

Figure 2: (Right) The cumulative velocity distribution function for the Local Group (black circles), the average of the six loose groups (red squares), and the Local Group including the CHVCs (green stars). The blue solid line represents the CDM model of Klypin roughly normalized to the second data point.

explains the decline in numbers across the last four bins for the loose groups. Concentrating instead on the four most massive bins, we can see that there is a rough agreement in the slopes of the Local Group and loose group HIMFs. This is still a very tentative result, which can be improved once we correct the lower mass bins for incompleteness. Generally, however, we do see that the Local Group and other analogous loose groups have similar HIMFs.

One of the main goals of this project was to see if the Local Group was unique in its relative lack of low-mass galaxies compared to the predictions of cold dark matter models, such as those of Klypin et al. (1999) and Moore et al. (1999). In Figure 2, we show the cumulative velocity distribution function (CVDF) for the Local Group (black circles) and the average of the six loose groups (red squares) as compared to the CDM simulation of Klypin et al. (1999) marked with the blue line. The CVDF describes the number of dark matter halos with a circular velocity greater than a given value; circular velocity is used as a surrogate for mass. It is immediately obvious that both the Local Group and the loose groups do not agree with the Klypin et al. (1999) simulations below $\sim$50 km s^{-1}, but agree almost perfectly with each other. Clearly whatever process is responsible for deficit of low-mass luminous halos, be it alternative forms of dark matter (e.g. warm dark matter Colín, Avila-Reese, & Valenzuela, 2000) or the suppression of baryonic collapse (e.g. Tully et al., 2002) or something else is not unique to the Local Group. Furthermore, given the similarities in the HIMF and the CVDF between the Local Group and our sample of loose groups, we believe that our sample groups are truly analogous to the Local Group.

3. High Velocity Clouds and Dark Matter Halos

Because our sample of loose groups appear to be true analogs to the Local Group, we can constrain the distance and mass of the CHVCs around the Milky Way. In Pisano et al. (2004), we determined that our non-detection of analogs to CHVCs with the properties proposed by Blitz et al. (1999); Braun & Burton (1999) down to our sensitivity limit implies that HVCs must lie within

D$\lesssim$160 kpc and have average HI masses of $\lesssim 4\times10^5 M_\odot$. This is in concordance with a variety of other observational and theoretical constraints (see Pisano et al., 2004, for further discussion), and suggests that the CHVCs are more closely associated with individual galaxies than with groups of galaxies.

These distance and mass limits do not, however, rule out the association of CHVCs with dark matter halos. On the contrary, they suggest a possible relation between CHVCs and low-mass dark matter halos. Simulations show that dark matter halos are also distributed within $\sim$100 kpc (Kravtsov, Gnedin, & Klypin, 2004). In addition, if we use the HWHM of the HI linewidths of CHVCs from de Heij, Braun, & Burton (2002a) and Putman et al. (2002), and equate it to the circular velocity of a putative dark matter halo, then we see on Figure 2 that CHVCs trace the CVDF predicted by Klypin et al. (1999) for CDM quite well. The deviation from CDM at small velocities is where the catalogs start to become incomplete. This coincidence of the spatial and mass distribution of the CHVCs and low-mass CDM halos provides circumstantial evidence that the CHVCs may be the missing dark matter satellites as originally suggested by Blitz et al. (1999).

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