Minihalos in and Beyond the Local Group

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1. Introduction

The ΛCDM paradigm which describes the evolution of structure predicts the existence of large numbers of low mass ($< 10^8$ to 10^9 $M_\odot$) halos. A cosmic census of such objects in the local neighborhood has in the last decade suggested that such objects are rarer than expected from numerical simulations, a problem often referred to with the label of "missing satellites" (Klypin *et al.* 1999l; Moore *et al.* 1999). Figure 1 illustrates the case, showing the dark matter distribution in the vicinity of a large, central galaxy resembling the Milky Way, surrounded by a hierarchy of lower mass halos. Observationally, this problem has been dramatized by both the scarcity of dwarf systems and the recent discoveries of circumgalactic fossil structures in wide field optical surveys such as 2MASS and SDSS.

While the gap between the number of features expected from numerical simulations and that obtained from observations has progressively narrowed, the number of known halos with circular velocities on order of $v_{circ} \simeq 20$ km s^{-1} or smaller remains still quite low. A widely adopted explanation of the mismatch is that gas accretion onto low mass halos is suppressed by reionization, which heats the gas, thus increasing the Jeans' mass; small mass halos are thus unable to accrete gas and to form stars (Ikeuchi 1986; Rees 1986). Numerical simulations by Hoeft *et al.* (2006) would indicate that halos with $M < 10^9$ $M_\odot$ are unable to retain the vast majority of their baryons (see Fig. 2). However, systems such as Leo T do exist (Ryan–Weber *et al.* 2008). At a distance of 420 kpc, Leo T is a star forming galaxy with an HI mass of 2.8×10^5 $M_\odot$, an HI radius of 300 pc, an indicative dynamical mass within the HI radius of $> 3.3 \times 10^6$ $M_\odot$ and a total mass to V-band luminosity within the HI radius > 56. Most of the baryonic mass is in the form of cold gas.

Ricotti (2008) points out that, as the intergalactic medium (IGM) cools and the degree of concentration of halos increases, gas accretion onto small halos can resume at lower z. He postulates that Leo T is an example of such a late bloomer. He also suggests that a fraction of the low mass halos, although able to accrete gas at low z, never make stars and can remain a population of baryon rich, starless systems to this day. Sternberg *et al.* (2002) and Maller & Bullock (2004) show that such systems could shield themselves from the metagalactic radiation field.

The broad question addressed by this paper concerns the validity of the ΛCDM galaxy formation paradigm in predicting the existence of large numbers of minihalos in galaxy groups and in voids; if so, are they detectable through the emission of their remaining baryons? We would like to know how common systems such as Leo T are and possibly answer the decades–old question of whether starless but sufficiently HI-rich minihalos exist.

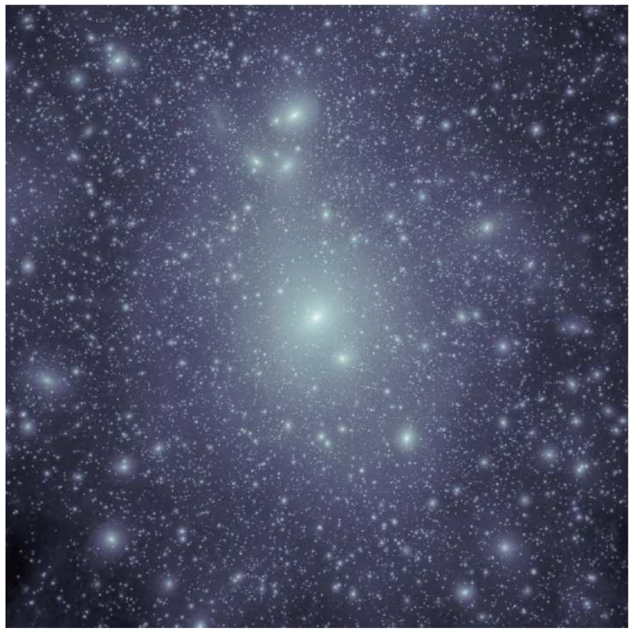

Fig. 1.— The ΛCDM galaxy hierarchy: N-body simulation of the distribution of dark matter halos of varying mass in the vicinity of a galaxy similar to the MW. Credit: Madau, Diemand & Kuhlen (2008).

2. Are High Velocity Clouds the Baryonic Counterparts of DM Minihalos?

High Velocity HI Clouds (HI) were discovered in the 1960s in the Netherlands (Muller *et al.* 1963). They have velocities that deviate from those expected for a differentially rotating Galactic disk and are found over a substantial fraction of the sky solid angle. They likely originate through a variety of processes, most of which were critically considered by Oort (1966). A thorough review of the subject is given by Wakker & van Woerden (1997). Some of the more extended HVC entities such as complexes A and C are a perigalactic phenomenon and lie at distances of order of 10 kpc (Wakker *et al.* 2007; 2008); the Magellanic Stream results from the interaction of the Magellanic Clouds with the Milky Way (MW) and lies

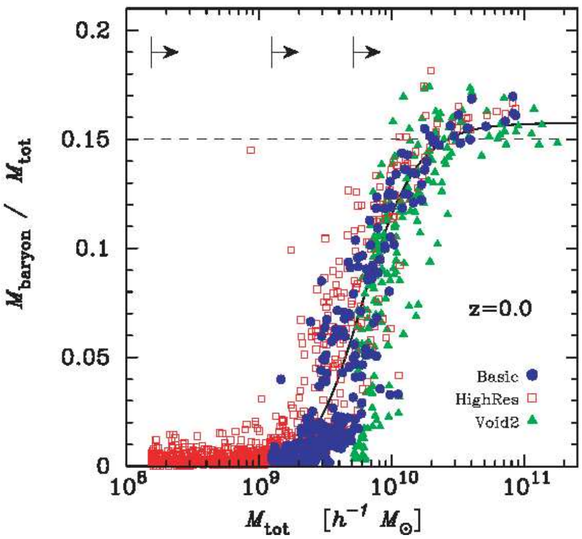

Fig. 2.— Remaining baryon fraction at $z = 0$ in DM halos of mass between 10^8 and 10^{11} $M_\odot$, from a simulation by Hoeft *et al.* (2006). Different colors refer to simulations of different mass resolution, red corresponding to the finest. It shows that halos with mass $< 10^9$ $M_\odot$ are generally unable to retain most of their baryons.

at distances of less than 100 kpc. These structures comprise a fair fraction of the HVC population, The distances of angularly less extended features are however far more uncertain and lack direct measurements. Some have been claimed to be satellites of Local Group galaxies (e.g. Thilker *et al.* 2004; Westmeier *et al.* 2005; Grossi *et al.* 2008) on grounds of angular and kinematical vicinity. Others, a population of more compact clouds, have been claimed as tracers of starless, low mass halos evenly spread over intergalactic space throughout the Local Group (LG). Early on, this idea was discussed in different guises by Oort (1966) and others (see review by Wakker & van Woerden 1997); more recently, it was forcefully revived by the work of two groups: Blitz *et al.* (1999) and Braun & Burton (1999). The first postulates that most HVCs are baryonic counterparts of LG minihalos, at typical distances of $\sim$ 1 Mpc; some are being accreted by the MW, tidally disrupted and appear as streamlike complexes. Quoting Blitz *et al.* : *"HVCs are large clouds, with typical diameters of 25 kpc, containing* 3×10^7 $M_\odot$ *of neutral gas and* 3×10^8 $M_\odot$ *of dark matter, falling towards* [the barycenter of] *the LG; altogether, the HVCs contain* 10^{10} $M_\odot$ *of neutral gas".* Braun & Burton (1999) refined the scenario by postulating that relatively unperturbed, intergalactic members of this population are identifiable with the so–called Compact HVCs (CHVC), a subset of the HVC population defined by their relatively small angular extent, compact morphology and apparent spatial isolation. Catalogs of several hundred CHVCs were produced by de Heij, Braun & Burton (2002) and Putman *et al.*

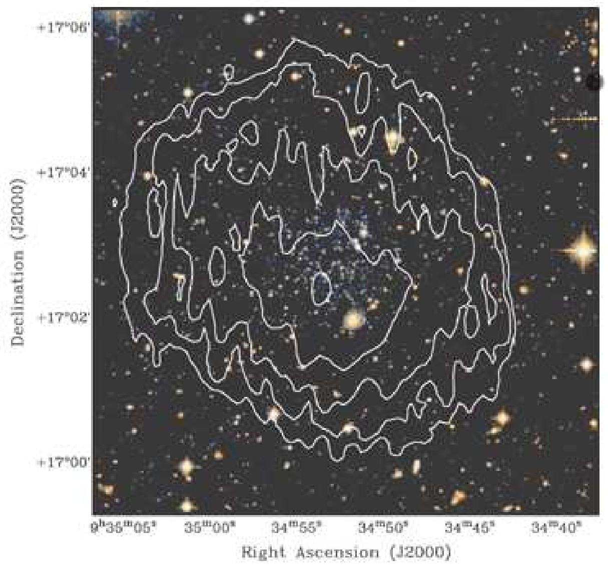

Fig. 3.— WSRT HI column density contours for Leo T, superimposed on an optical image (after Ryan-Weber *et al.* 2008).

(2002), respectively from the Leiden–Dwingeloo Survey (LDS; angular resolution $\simeq 0^\circ.5$) and the Parkes (HIPASS; angular resolution $\simeq 0^\circ.25$) survey. Burton, Braun & Chengalur (2001) obtained higher angular resolution ($\simeq 3.5'$) images of several CHVCs with the Arecibo telescope: using a variety of criteria based on morphological and spectral parameters of the clouds, they obtained "soft" estimates of cloud distances varying between 150 and 850 kpc.

Sternberg, McKee and Wolfire (2002) have argued against the idea by raising two important objections:

- First, if the halos of the HVCs are assumed to have concentration indices comparable with those of very low mass dwarf galaxies in the LG such as Leo A, Leo T and SagDIG, then the much larger angular sizes of the CHVCs force them to be placed at distances of order 150 kpc rather than 1 Mpc. In order for the CHVCs to be at typical LG distances, their minihalos would have to be extremely under–concentrated with respect to those of dwarf galaxies of comparable mass and thus violate the relatively tight scaling relation between halo mass and concentration index of the ΛCDM galaxy formation paradigm.

- Second, if in spite of the previous objection underconcentrated halos were fit to the CHVCs assumed at Mpc distances, the resulting gas distributions would have very low pressures and huge peripheral masses of warm ionized gas surrounding the small neutral medium at the center. This configuration would suppress neutral multiphase cores, as at lower densities recombinations become rarer. Another unwelcome result of this halo configuration in models is that the gas mass (neutral plus ionized) to dark matter ratio would have to exceed the cosmological value of $\sim 1/5$.

Bottom line: the angular sizes of the CHVCs are too large to be accomodated as isolated LG dwellers. Sternberg *et al.* (2002) favor a circumgalactic solution, whereby the Braun & Burton type of CHVC would be located within 150 kpc in the MW halo.

The idea of HVCs and CHVCs as LG minihalos runs also in an important observational problem. If present, such objects would have been detectable by deep surveys of nearby groups, such as that of Pisano *et al.* (2007), which had a sensitivity of $\sim 10^7$ $M_\odot$. They were not, raising the objectionable prospect of uniqueness of physical characteristics for the putative LG minihalos.

3. New Observations

The currently ongoing Arecibo Legacy Fast ALFA survey (ALFALFA; Giovanelli *et al.* 2005) aims to map 7000 square degrees of high galactic latitude sky in the HI 21cm line, covering the spectral range between 1335 and 1435 MHz (roughly -2500 km s^{-1} to 17500 km s^{-1} for the HI line), with a spectral resolution of ~ 5 km s^{-1} . With a spatial resolution of $\sim 3'.5$, ALFALFA resolves structures of 1/4 to 1/9 the angular size possible with previous HVC surveys and reaches nearly one order of magnitude deeper in flux. ALFALFA can detect $\sim 5 \times 10^4$ $M_\odot$ of 20 km s^{-1} linewidth at a distance of 1 Mpc. As of early 2009, 25% of the ALFALFA survey data have been fully processed; mostly, they correspond to a broad region of 1700 square degree near the North Galactic Cap. Several dozen HVCs are found in this region, most of which were previously unknown. Many of the clouds have sizes of less than 15', some are unresolved by the $\sim 4'$ Arecibo telescope beam. Their distances are unknown. A subset of these objects contains credible, starless minihalo LG candidates: with HI masses between 10^5 to 10^6 $M_\odot$ and HI sizes of ~ 1 kpc at 1 Mpc distance, they do not violate physical constraints imposed by the structure formation paradigm, they are found at a number consistent with the expectations of abundance of low mass halos, as drawn from numerical simulations and they could not have been detected by previous experiments in nearby galaxy groups at current sensitivity limits. However, the difficulty of unambiguously discriminating them from Galactic or circumgalactic features remains. The clinching evidence that such systems exist will be their detection in other galaxy groups, well separated in velocity from the range of galactic and perigalactic phenomena. Fortunately, technology developments should soon make it possible for new experiments to test the existence of such systems in environments other than the Local Group.

4. Future Prospects

The detectability of the putative HI minihalos discussed above depends on telescope sensitivity, spectral resolution and sky coverage of blind surveys. The combination of those parameters delivers a survey figure of merit or survey speed. The Arecibo 305m telescope is the most sensitive HI machine in the world. Its 7–feed ALFA system delivers instantaneous coverage of a solid angle equal to 7 beams. Square Km Array (SKA) precursor telescopes currently under design or construction will, within a few years, achieve survey speeds a few times faster than the Arecibo+ALFA combination, thanks to their multibeaming capabilities. Plans to build a 40–beam phased focal plane array — referrred to as AO40 — at Arecibo are afoot, which will allow the 305m dish to achieve a survey speed equal to those of the SKA precursors. Requiring a single focal plane array rather than one for each of the telescopes in a distributed aperture, allowing well exercised options for commensal observing and posing a much lower demand on correlator capacity and data volume, the AO40 device will more effectively be optimized for high performance, and of course the telescope already exists and is a well understood, honed system. The prospects for deeper HI surveys than ALFALFA in the near future are thus exciting.

In order to detect narrow–lined HI sources of less than 10^6 $M_\odot$ at the 5–10 Mpc distance range of neighboring galaxy groups, a sensitivity one order of magnitude higher than ALFALFA's will be required. In order to cover sufficiently large sky areas in nearby groups and cosmic voids at that sensitivity level, on order of 10^3 hours of telescope (AO40 or SKA precursor) time will be required. Angular resolution of currently planned distributed apertures will be a relatively unimportant discriminant, as minihalos will be effectively unresolved at 5–10 Mpc distances by AO40 and SKA precursors. This type of survey, which would deliver data sets of interest to many other scientific fields, will be possible before the middle of the decade.

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