ARE NEWLY DISCOVERED H I HIGH-VELOCITY CLOUDS MINIHALOS IN THE LOCAL GROUP?

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ABSTRACT

A set of H I sources extracted from the north Galactic polar region by the ongoing ALFALFA survey has properties that are consistent with the interpretation that they are associated with isolated minihalos in the outskirts of the Local Group (LG). Unlike objects detected by previous surveys, such as the compact high-velocity clouds of Braun & Burton, the H I clouds found by ALFALFA do not violate any structural requirements or halo scaling laws of the ΛCDM structure paradigm, nor would they have been detected by extant H I surveys of nearby galaxy groups other than the LG. At a distance of <3 Mpc, their H I masses range between 5 × 10^6 d^2 and 10^7 d^2 M☉ and their H I radii between <0.4d and 1.6d kpc. If they are parts of gravitationally bound halos, the total masses would be on the order of 10^9–10^10 M☉, their baryonic content would be significantly smaller than the cosmic fraction of 0.16 and present in a ionized gas phase of mass well exceeding that of the neutral phase. This study does not however prove that the minihalo interpretation is unique. Among possible alternatives would be that the clouds are shreds of the Leading Arm of the Magellanic Stream.

Key words: galaxies: distances and redshifts – galaxies: halos – galaxies: luminosity function, mass function – galaxies: photometry – galaxies: spiral – radio lines: galaxies

1. INTRODUCTION

The ΛCDM paradigm which describes the evolution of structure predicts the existence of large numbers of low mass (≤10^8 M☉) halos. A cosmic census of dwarf galaxies at z = 0 indicates that such objects are rarer than expected from numerical simulations. In different guises, this circumstance has been referred to as the “void phenomenon” (Peebles 2001) or the “missing satellite” problem (Klypin et al. 1999; Moore et al. 1999). The gap between the number of Milky Way (MW) satellites expected from numerical simulations and that obtained from observations has progressively narrowed in recent years with the discovery of fossil stellar structures in optical wide-field surveys. While this technique has detected numerous dwarf satellites of the MW, no gas-rich systems have been found and the number of known halos with circular velocities of v_circ ≤ 20 km s^{-1} located in the general field remains very low. As is the case with the luminosity function of optical galaxies, the mass function of extragalactic H I sources also has a faint end slope much shallower than predicted by the Press–Schechter formalism (Zwaan et al. 2006; A. Martin et al. 2009, in preparation). H I surveys are thus not detecting enough low mass sources to significantly alleviate the observed paucity of dwarf galaxies.

Early on after their discovery, the possible extragalactic nature of H I high-velocity clouds (HVCs) was considered (see previous work reviewed by Wakker & van Woerden 1997). More recently, the idea was forcefully revived by two groups: Blitz et al. (1999) and Braun & Burton (1999). The latter postulated that the so-called Compact HVCs (CHVCs), a subset of the HVC population defined by a relatively small angular extent and apparent spatial isolation, are the baryonic counterparts of isolated, low mass halos distributed across the Local Group (LG). Hereafter we shall refer to this idea as the “minihalo/HVC hypothesis.” Two important problems mire this idea. The first is that if present in other nearby groups of galaxies, CHVCs could have been detected by extant H I surveys; they have not (e.g., Pisano et al. 2007). The second is that the structural properties of the CHVCs are inconsistent with those expected for low mass halos, according to the ΛCDM structure formation scenario, as pointed out by Sternberg et al. (2002, hereafter SMW02): as minihalos, CHVCs appear underconcentrated, and at typical LG distances—on the order of 1 Mpc—they would be too large.

A widely adopted explanation of the discrepancy between the numbers of observed and predicted dwarf galaxies is that gas accretion onto low mass halos is suppressed by the intergalactic UV radiation field (Ikeuchi 1986; Rees 1986; cf. Huet et al. 2006). In their Mare Nostrum simulations, the latter show that the baryon to total mass fraction may fall steeply with redshift from the cosmic value of ~0.16 to only a few percent between halo masses 10^10 M☉ and M < 10^9 M☉. SMW02 showed that most of the gas in low mass halos should be found in a thermally stable, ionized phase which envelopes a warm but neutral and stable component of much lower mass. Within the latter, a cold core may be able to form and partially convert into stars. A 10^9 M☉ halo may thus contain fewer than 10^7 M☉ in a phase detectable optically or via its 21 cm emission, thus explaining the paucity of such objects in wide-field surveys. The simulations by Ricotti (2009) somewhat improve the observational prospects: he points out that, as the universe expands, the intergalactic medium (IGM) cools and the UV radiation background is diluted; changes in the IGM Jeans mass and the halo mass concentration then may make it possible for a previously “dormant” low mass halo to resume accreting gas at low z. He proposes that the recently discovered, nearby dwarf galaxy Leo T (Irwin et al. 2007) may be such an object.
However, the currently ongoing Arecibo Legacy extragalactic dynamical mass within the H I component exist. If they do, the safest place to look for them is away from a massive galaxy like the MW. We found them, but we still treat the minihalo interpretation with skepticism until the detection is achieved of (1) a stellar counterpart, (2) an internal velocity field that more reliably reveals a dynamical mass than a plain line width, or (3) analogous objects in other galaxy groups.

2. OBSERVATIONS

We report on the results of 21 cm H I observations, made with the Arecibo 305 m radio telescope as part of the ALFALFA survey. They cover the region between $9.5^h < \text{R.A.} < 16.5^h$, $+4^\circ < \text{decl.} < +16^\circ$, of approximately 1300 deg$^2$, with a spectral resolution of $\sim 5.5$ km s$^{-1}$, an angular resolution of $\sim 3/5$, and a sensitivity such that an H I mass of $\lesssim 5 \times 10^4 M_\odot$ can be detected at 1 Mpc distance. A full description of the observational mode of ALFALFA is given in Giovanelli et al. (2005), while the definition and goals of the survey are described in Giovanelli et al. (2007). Many aspects of the processing pipeline are described in Saintonge (2007) and Kent (2008).

The chosen region of the sky is a strip extending between $b = 35^\circ$ and $b = 80^\circ$ in the north Galactic polar cap, well suited to minimizing the kinematical intrusion of Galactic H I. Within that region, we searched for sources not associated with known galaxies with the following additional criteria: (1) heliocentric velocity $V_0 > 120$ km s$^{-1}$ or $V_0 < -110$ km s$^{-1}$ (the $V_0$ range between $-110$ and $+120$ km s$^{-1}$ was excluded in order to avoid confusion with Galactic emission), (2) major H I diameter $\lesssim 15^\prime$, (3) no visible low surface brightness connection to features in the $-110$ to $+120$ km s$^{-1}$ range. Twenty-one ultracompact clouds (hereafter UCHVCs) with positive velocities (six are unresolved) and six clouds with negative velocities were found. All sources detected by ALFALFA with a signal-to-noise S/N $< 10$ were re-observed and confirmed. Figure 1 shows an integrated flux map and a line profile of one of the detections. A catalog with a detailed description of individual sources is presented in R. Giovanelli et al. (2009, in preparation). Table 1 displays the mean and range values for the properties of the 27 clouds, scaled by the unknown distance in Mpc, namely: the range in heliocentric velocities for positive and negative velocity clouds, in km s$^{-1}$; the full line width at half-power $W$, of generally Gaussian shape; the mean radius at the isophote encircling 50% of the flux $R_{50}$ in kpc; the log$_{10}$ of the H I mass and of the total mass within $R_{50}$, in solar units; the crossing time $t_{\text{cross}} = 2R_{50}/W$ in Gyr. On the assumption that the clouds are parts of self-gravitating systems, the total mass is estimated via

$$M_{\text{vel}}(< R_{50}) \simeq R_{50}\sigma^2/G$$

(1)

| Property | Average | Range |
|----------|---------|-------|
| $V_0$, positive (km s$^{-1}$) | 124.320 |       |
| $V_0$, negative (km s$^{-1}$) | $-118$ to $-142$ |       |
| $W$ | 24 km s$^{-1}$ | 16.56 |
| $R_{50}$ | 0.75 kpc | <0.4:1.6 |
| $\log[M_{\text{HI}}/M_\odot]$ | 5.25 | 4.75:5.97 |
| $\log N_{HI}$ (cm$^{-3}$) | 19.10 | 18.80:19.58 |
| $\log[M_{\text{HI}}(<R_{50})/M_\odot]$ | 7.35 | 6.83:7.77 |
| $t_{\text{cross}}$ | 0.08 Gyr | 0.02:0.32 |

At a distance of 420 kpc, Leo T is a star-forming galaxy with an H I mass of $2.8 \times 10^8 M_\odot$, an H I radius of 300 pc, an indicative dynamical mass within the H I radius of $\sim 3.3 \times 10^8 M_\odot$, a total mass to V-band luminosity within the H I radius of 56, and a stellar mass of $\sim 1.2 \times 10^5 M_\odot$ (Ryan-Weber et al. 2008; see also Grcevich & Putman 2009).

The precipitous drop in the cold baryon fraction for halos of mass $\lesssim 10^{10} M_\odot$ proposed by the simulations by Hoeft et al. and the models of SMW02 can explain the shallow slopes of the low end of optical and H I luminosity functions. It also indicates that the minihalo/HVC hypothesis could only apply to sources of more extreme properties than previously thought: H I masses of $\lesssim 10^5 M_\odot$, sizes of $\lesssim 1$ kpc and line widths of $\lesssim 30$ km s$^{-1}$. The requirements for detection of such sources are very challenging, exceeding the combination of sensitivity and spectral resolution of most large-scale extragalactic H I surveys. However, the currently ongoing Arecibo Legacy extragalactic H I survey (ALFALFA) offers an opportunity for detection of systems matching the requirements mentioned above, albeit only to distances of a few Mpc. The question motivating this.
with $\sigma = W/2\sqrt{2\ln 2}$. The “minimum intrusion” approach (Giovanelli et al. 2005) adopted for data taking by ALFALFA delivers exceptional bandpass stability and allows reliable recovery of flux and size estimation for the UCHVCs.

The possibility of extended envelopes of diffuse gas below the column density limit of the survey cannot however be excluded.

The sky distribution of the UCHVCs is shown in Figure 2. Also plotted are the locations of galaxies with primary distances of $\leq 2.6$ Mpc, as listed in the Catalog of Nearby Galaxies (Giovanelli et al. 2004). Those galaxies are, respectively, from west to east: D634-03, Leo T, Sex B, Leo I, GR8, KKH86 and DDO 187. All but Leo I (the nearest at $d = 0.25$ Mpc) are detected in H1. Leo T and DDO 187 are just outside the decl. range of the H1 clouds. Figure 3 shows the location of clouds and nearby galaxies in the Galactic longitude versus velocity in the galactic standard of rest plane, where $V_{\text{lsr}} = V_{\text{vir}} + 225 \sin l \cos b$ and for $V_{\text{vir}}$ we assume a solar motion of $20$ km s$^{-1}$ toward $l = 57^\circ$, $b = 25^\circ$. The three negative velocity clouds near RA = 16$^h$ could possibly be associated with the extended, perigalactic HVC complexes A and M.

3. DISCUSSION

The sky and velocity distributions of the clouds found by ALFALFA match well that of dwarf galaxies in the LG. If placed at $d = 1$ Mpc, the UCHVCs are compact and do not violate any structure predictions of the LCDM scenario emphasized by SMW02. Their H1 masses, $\lesssim 10^6 M_\odot$, would make them undetectable by previous H1 surveys of nearby groups, such as that of Pisano et al. (2007). Thus, the minihalo/HVC hypothesis could apply without posing the observational requirement of LG uniqueness. H1 surveys of nearby groups reaching a sensitivity level of $10^6 M_\odot$—about an order of magnitude more sensitive than ALFALFA—would be necessary to verify the possible existence of similar systems elsewhere than the LG. Such observations are currently challenging but possible with foreseen upgrades to current instrumentation.

The mean parameters of the UCHVCs at $d = 1$ Mpc are a good match for SMW02 minihalo models with a Burkert density profile, $R_{\text{vir}} \simeq 0.7$ kpc, $M_{\text{vir}} \simeq 3 \times 10^5 M_\odot$, total to neutral gas mass ratio of 15, peak $N_{\text{H1}} \simeq 4 \times 10^{19}$ cm$^{-2}$, total halo mass $M_{\text{vir}} \simeq 3 \times 10^6 M_\odot$, surrounded by a hot, ionized IGM of pressure $P_{\text{HIM}} = 10$ cm$^{-3}$ K. The peak $N_{\text{H1}}$ predicted by the models is higher than, but not incompatible with the observed values shown in Table 1, as the latter are averaged over the radius of the clouds and smeared by the $\sim 3.5$ beam of the Arecibo telescope. The $M_{\text{vir}}$ inferred from the observations are about one order of magnitude smaller than the model’s $M_{\text{vir}}$; yet the two are consistent with each other since the values inferred from the observations are estimates of the masses within $R_{\text{H1}}$. As the cold baryons dissipatively collapse to the bottom of the halo potential well, the extent of the dark matter halo exceeds that of the cold gas by a factor of several, explaining the mass discrepancy.

A further test of the minihalo/HVC hypothesis relates to the number of minihalo candidates expected from simulations. The cumulative halo mass function $N(M)$ is a power law of approximate slope $M^{-0.86}$ (e.g., Figure 6 of Gottloeber et al. 2003). Figure 4 of Hoeft et al. (2006) shows the transition in the baryon fraction of halos dropping from the cosmic value of 0.16 to less than 0.02 over a decade in halo mass, around the “characteristic mass” $M_{\text{char}} \simeq 10^{9.8} M_\odot$, for which halos are able to retain half their baryons. If we assume that the UCHVCs pertain to the category of halos of mass between $M_{\text{char}}$ and $M_{\text{char}}/\delta_M$, and that the $N_{\text{opt}}$ optical galaxies in the field are hosted by halos with $M > M_{\text{char}}$, then we can estimate the ratio between the numbers of the two kinds of objects as $f_n = N_{\text{opt}}/N_{\text{cloud}} \simeq \delta_M^{-1}$, with $\delta_M > 1$. The range in dynamical masses estimated for UCHVCs is about one order of magnitude (see Table 1); assuming that the corresponding, putative halo masses are spread just as narrowly, we guess $\delta_M \simeq 10$. There are five galaxies with $d \leq 2.6$ Mpc in the region in which the clouds were observed, and the exclusion of the spectral region $120 > V_\odot > -110$ km s$^{-1}$ in our search due to confusion with Galactic emission blanks about 50% of our search volume. The expected number of minihalos is then $\sim 5 \times 10^{0.86}/2 \sim 18$. We identified 27 clouds. Given the crudeness of the calculation, our cloud detection rate appears compatible with a minihalo/HVC scenario. Next we ask: what else could the clouds be?

In a Galactic fountain (Shapiro & Field 1976), gas is accelerated by strong stellar winds and supernova explosions in the disk and is ejected to the Galactic halo to z-heights of a few kpc; gas clouds then cool and “rain back” onto the disk. At a distance of 3 kpc from the Galactic plane, the clouds’ H1 masses would be near solar, their sizes on the order of 1 or a few pc and crossing times less than 1 Myr, much shorter than the ballistic timescales of 50–100 Myr. Our cloud sample is extracted from the Galactic polar region, the component of the clouds’ veloci-
ties perpendicular to the Galactic plane is dominant. Velocities in excess of 200 km s$^{-1}$ are difficult to accommodate within a galactic fountain scenario with currently assumed values for the density of a galactic corona (e.g., Fukugita & Peebles 2006; Grechnev & Putman 2009): small clouds would rapidly decelerate due to ram pressure, and MW tidal forces would eventually disrupt them.

Our survey region overlaps with the so-called field of streams (Belokurov et al. 2006), containing part of the tidally disrupted remnants of dwarf spheroidal MW satellites, namely, the Sag and Orphan streams. With velocities between +20 and −100 km s$^{-1}$, their kinematics are very different from those of most of the H$_{\text{I}}$ clouds, and an association is unlikely.

The Magellanic Stream is witness of the tidal disruption of the Magellanic Clouds by the MW. Most of the Stream is antipodal to the northern Galactic polar region. However, its so-called Leading Arm (LA) extends to the northern Galactic hemisphere up to $b \approx 35^\circ$, with velocities reaching +250 km s$^{-1}$. If the UCHVCs are a northern extension of the LA, according to the tidal model of Connors et al. (2006; see also McClure-Griffiths et al. 2008) they would be at distances of an order of 100 kpc, have masses on the order of $10^3 M_{\odot}$ and crossing times of $\sim$10 Myr. Tidal and ram pressure forces would be mild. This is a plausible scenario, although the LA would then extend twice as far and forward of the Magellanic Clouds than previous observations indicated.

Galaxies grow via mergers and intergalactic gas infall. Infalling gas can be shock-heated to the virial temperature of the halo or fall at colder temperatures. Simulations show that the cold accretion mode tends to be more important for small mass halos: for a galaxy like the MW, $\approx$90% of gas accretion is thought to take place in the hot mode (Keres et al. 2009; Dekel et al. 2009). Sancisi et al. (2008) discuss the evidence for extraplanar H$_{\text{I}}$ in several nearby galaxies and interpret it as resulting from a combination of mergers of gas rich satellites and cold gas accretion. In their H$_{\text{I}}$ maps, the extraplanar gas is seen at distances of 15 kpc or less from the main galaxy. Two difficulties arise with a model whereby our clouds are a manifestation of a similar phenomenon. First, the objection raised in the discussion of the galactic fountain scenario, that the clouds are too small, vulnerable and short-lived, holds in this case as well. Second, as shown by Maller & Bullock (2004), thermal instability and conduction prevent the cooling of infalling gas on scales smaller than the so-called field length, which for the galactic corona translates into a mass of $\sim 10^6 M_{\odot}$. At perigalactic distances of $\sim$100 kpc or less, our clouds would be much smaller than that limit.

In conclusion, we report the discovery of a category of HVCs which are plausible minihalo candidates. They have properties and are found in numbers which are compatible with theoretical expectations for halos with masses $\lesssim 10^5 M_{\odot}$ and could not have been detected by extant H$_{\text{I}}$ surveys beyond the LG. However, it is not yet possible to exclude that they may be part of the wider scenario of the yet relatively poorly understood perigalactic HVC phenomenon. While difficulties arise in their interpretations with several more frequently invoked models, reasonable adjustments could be made to fit some of them, most notably the possibility that they are an extension of the LA of the Magellanic Stream. We have thus discovered a category of objects consistent with the minihalo/HVC hypothesis, but we have not proved that such interpretation is unique.

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