Poster Contributions

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Ultra-Compact High Velocity Clouds as Minihalos and Dwarf Galaxies

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Abstract. We present dark-matter minihalo models for the Ultra-Compact High Velocity HI Clouds (UCHVCs) recently discovered in the 21 cm ALFALFA survey. We assume gravitational confinement of $\sim 10^4$ K HI gas by flat-cored dark-matter subhalos within the Local Group. For the UCHVCs we calculate the photoionization-limited hydrostatic gas profiles for any distance-dependent total observed HI mass and predict the associated (projected) HI half-mass radii. The observed 21 cm fluxes and half-mass angular radii then constrain the source distances or DM halo parameters. As a consistency check we model the gas-rich dwarf galaxy Leo T, for which the distance is known (420 kpc) and there is a well-resolved HI column density profile. We derive an upper limit for the pressure of any enveloping hot IGM gas at the distance of Leo T. Our analysis supports the scenario that some of the UCHVCs may constitute a population of 21-cm-selected but optically-faint dwarf galaxies in the Local Volume.

Keywords. galaxies: evolution, galaxies: formation, galaxies: dwarf, galaxies: halos, Local Group, dark matter, radio lines: galaxies

1. Motivation

Recent sensitive and high-resolution 21 cm observations, carried out as part of the ALFALFA survey (Giovanelli *et al.* 2005; Haynes *et al.* 2011) have revealed a population of isolated Ultra-Compact High-Velocity Clouds (UCHVCs, Giovanelli *et al.* 2010; Adams *et al.* 2013, hereafter G10 and A13). With angular diameters of $\lesssim 10$ arcmin, the UCHVCs are significantly smaller than the $\sim 1°$-sized CHVCs, discussed and analyzed by Braun & Burton (1999); Blitz *et al.* (1999) and by Sternberg *et al.* (2002, hereafter SMW02). The UCHVCs are isolated kinematically and spatially from the well-studied and extended HVC complexes (Oort 1970; Putman *et al.* 2012). The A13 UCHVC catalogue contains ~ 60 objects found in data covering $\sim 2,800$ square degrees. The survey does not provide any distance constraints, and the locations of the UCHVCs are unknown. G10 and A13 have suggested that some of the newly discovered UCHVCs might be low-mass optically faint dwarf galaxies that are sufficiently gas rich to be detectable 21 cm sources within the Local Volume (see also Saul *et al.* 2012). Leo P, the first dwarf galaxy discovered in 21 cm as a UCHVC, supports this scenario. Optically dark but gas-rich galaxies may be useful in addressing basic questions related to structure and galaxy formation at small scales - the number of dwarf galaxies, the effect of stellar feedback on halo properties, star formation at low metalicities and the properties of dark matter (Tollerud *et al.* 2008; Zolotov *et al.* 2012; Skillman *et al.* 2013; Rocha *et al.* 2013; Zavala *et al.* 2013; Tollerud & Peek 2018).

2. Our Model

In the work summarized here (Faerman *et al.* 2013, hereafter FSM13) we model Leo T and the UCHVCs as spherical, non-rotating, thermally supported HI clouds confined by the gravity of low-mass dark matter (DM) halos. For this purpose we employ and extend the minihalo model, presented in SMW02. We assume an isothermal warm ($\sim 10^4$ K) gas in hydrostatic equilibrium. The gas is heated and ionized by the present-day metagalactic radiation field (SMW02, Haardt & Madau 2012). We solve for the coupled hydrostatic and ionization structure, for the warm HI surrounded by ionized shielding envelopes. This enables predictions for the observable HI column density profiles and total HI masses as functions of the assumed DM density profiles and gravitational potential wells. We assume the clouds are embedded in distant ($d \gtrsim 300$ kpc) and unstripped subhalos, and use the cosmological concentration relation derived from the *A*quarius simulation (Springel *et al.* 2008). About 20 of the ~ 60 UCHVCs in the A13 catalogue are only marginally resolved, and these compact sources are the focus of our study. Their HI masses are in range $(1.4 - 4.2) \times 10^5 d_{\rm Mpc}^2$ M$_\odot$, where $d_{\rm Mpc}$ is the distance in Mpc.

3. Results

(*a*) **Strigari mass explained?**
We assume flat-core (Burkert 1995) density profiles for the DM halos, motivated by evidence for flat cores in Local Group dwarf galaxies (Gentile *et al.* 2004; de Blok *et al.* 2008; Walker & Peñarrubia 2011. We find that for median cosmological concentrations (Springel *et al.* 2008), Burkert profiles naturally give rise to the common mass scale of $\sim 10^7$ M$_\odot$ within 300 pc (M_{300}), observed in nearby Milky Way satellites (the "Strigari mass", Strigari *et al.* 2008). Fig. 1 shows M_{300} as a function of the halo scale velocity for flat-core and cuspy (NFW, Navarro *et al.* 1997) profiles. Furthermore, as suggested in FSM13, flat-core DM profiles may also resolve the Too-Big-to-Fail problem (Boylan-Kolchin *et al.* 2011; Bullock & Boylan-Kolchin 2017.

(*b*) **HI profile in Leo T**
We fit the observed HI gas distribution in the gas-rich dwarf galaxy Leo T (Irwin *et al.* 2007, $d \sim 420$ kpc and $M_{\rm HI} \sim 3 \times 10^5$ M$_\odot$). This serves as a proof-of-concept for our minihalo models. We adopt the column density profile of warm HI measured by Ryan-Weber *et al.* (2008) and find that it is best fit by DM halos with $M_{300} \sim 8 \times 10^6$ M$_\odot$ (see Fig. 2). This result is consistent with the mass estimated from the dispersion in stellar velocities and with the common mass scale Strigari *et al.* 2008. The observed extent of the HI profile also sets an upper limit on the ambient hot intergalactic medium gas pressure ($P_{\rm HIM}$) at the distance of Leo T, with $P_{\rm HIM}/k_{\rm B} \lesssim 150$ cm^{-3} K (see also Faerman *et al.* 2017).

(*c*) **Predicting UCHVC distances**
The HI masses of the clouds in our models vary as the distance squared, $M_{\rm HI} \propto d^2$, and set the physical cloud sizes. The angular radius containing half the projected HI mass (or flux), $\theta_{1/2}$, can then be used to predict the UCHVC distances. We construct a relation between the distance and the half-flux angular radius for clouds with a constant 21 cm flux, typically ~ 1 Jy km s^{-1} for the UCHVCs. The results,

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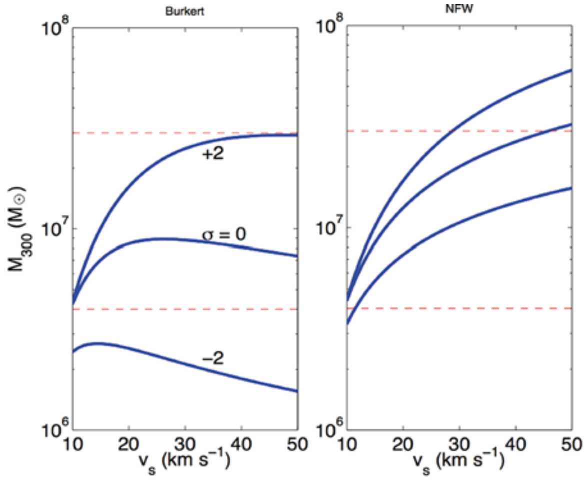

Figure 1. The total mass inside 300 pc as a function of the halo scale velocity, for the flat-core Burkert (left) and the cuspy NFW (right) profiles. σ is the number of standard deviations from median cosmological halos. The dashed horizontal lines mark the range of the common mass scale in MW dwarf satellites.

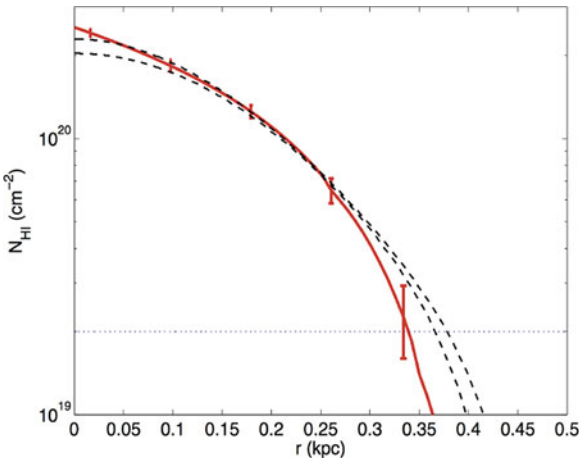

Figure 2. The observed HI column density profile in Leo T (solid red, with errors, measured by Ryan-Weber *et al.* 2008), and the profiles of the best fit models (dashed), using a flat-core DM halo. The dotted horizontal line marks the 3σ detection sensitivity limit.

presented in Fig. 3, can be approximated by a power-law function for the distance as a function of the HI cloud angular size and the DM halo concentration

$$d = 0.91 \times 10^{-0.15\sigma} \times \left(\frac{\theta_{1/2}}{1'}\right)^{-1.47} \text{ Mpc} \quad . \tag{1}$$

This expression is accurate to within 10% for σ between -1 and $+1$. FSM13 show how this relation varies for objects with different 21 cm fluxes.

(*d*) Leo P as a minihalo

For Leo P the distance is known from optical observations (McQuinn *et al.* 2013), which place it at $d \sim 1.72$ Mpc. Given the 21 cm flux ($S_{21} \sim 1.3$ Jy km s^{-1}, or $M_{\rm HI} \approx 9.5 \times 10^5$ M$_\odot$) and size ($\theta_{1/2} \sim 1'$), measured by Giovanelli *et al.* (2013), we can infer the halo properties. The implied best fitting parameters for unstripped halos are $\sigma \sim -2$ and $M_{300} \sim 10^6$ M$_\odot$ (see marker in Fig. 3).

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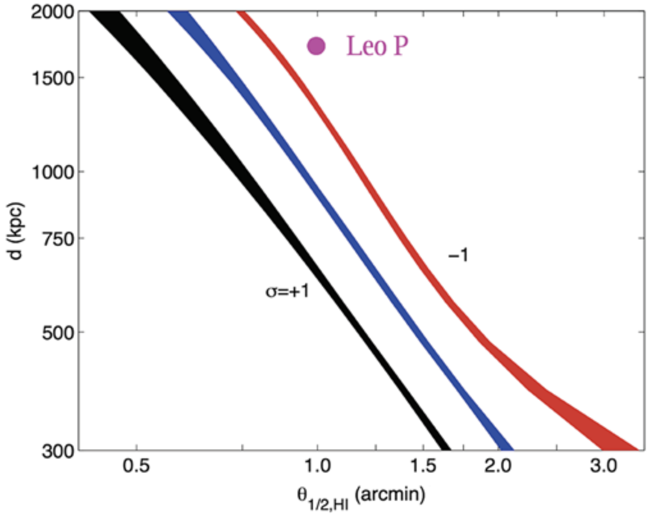

Figure 3. Size-distance relation for minihalos with a constant 21 cm flux. The relation is shown for median cosmological halos (middle, blue curve) and over- and under-concentrated halos with $\sigma = +1$ and -1 (black and red, respectively). The marker shows Leo P, at a distance of ~ 1.72 Mpc and $\theta_{1/2} \sim 1$ arcmin, suggesting a DM halo with $\sigma \sim -2$.

4. Future Work

Ongoing and future high resolution 21 cm observations of the most compact UCHVCs (Adams *et al.* 2016), and searches for stars in these objects (Sand *et al.* 2015; Janesh *et al.* 2017, will enable to use our models to constrain the distances to the sources or the properties of the confining DM halos. This will provide a new method to study the properties of low-mass galaxies through their gas distributions.

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