Astro2020 Science White Paper

Invisible Structures in the Local Universe

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation

☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics

☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments

☒Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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Abstract (optional):

Neutral hydrogen (HI) surveys have revealed the existence of dark and almost-dark structures around nearby galaxies and in local groups and clusters. Understanding these structures will give us insights into how hydrogen – the basic fuel of star formation – cycles in and out of galaxies in different environments and will help us to understand the occupancy of low-mass dark matter subhalos.

Invisible Structures in the Local Universe

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Circumgalactic environment

Single dish surveys of the larger galaxies in the Local Group (M31; Wolfe et al. 2016, M33; Grossi et al 2008; Keenan et al. 2016) found populations of HI clouds surrounding these galaxies, possibly similar to the high velocity clouds (HVCs) around our own Galaxy, that could provide a link to the 'missing galaxy' problem, i.e. they could be dark matter subhalos that contain HI but at a density too low for start formation. Keenan et al. (2016) also found an enigmatic ring of HI near to – and about the same angular size as – M33, the origin of which remains unexplained (Figure 1).

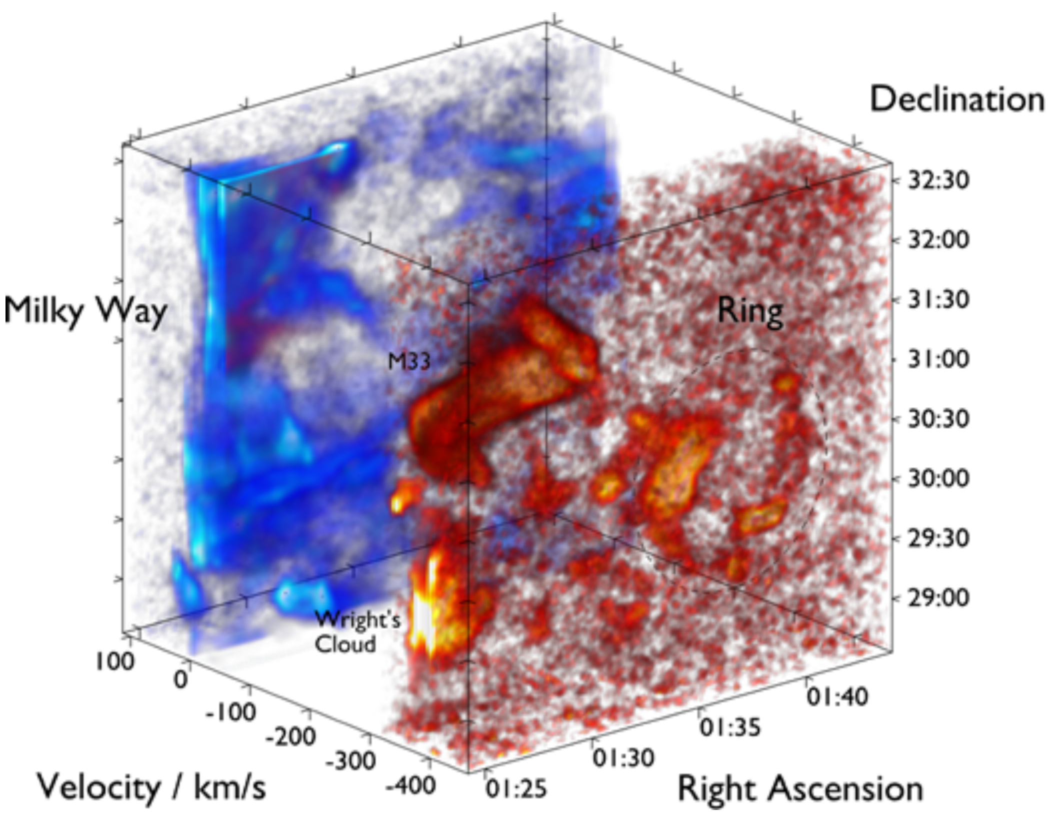

Figure 1. "Keenan's Ring" near M33, with Wright's Cloud visible near the edge of the datacube (from Keenan et al. 2016; Fig. 1)

Also in the Local Group, Wolfe et al. (2013) found that the HI bridge found between M31 and M33 by Braun & Thilker (2004) was 50% composed of condensed clouds with the remainder being diffuse gas and concluded that this bridge was probably condensations on an intergalactic filament that could be feeding gas via cold-mode accretion into both galaxies and fueling their star formation.

In the next decade, we want to push such studies outside of the Local Group to examine the circumgalactic environments of galaxies in the local universe (c.f. Pisano et al. 2018). This would allow the number and sizes of HI clouds typically found around galaxies to be characterized, providing key data points for comparison with cosmological simulations, as well as potentially identifying other possible cold-mode accretion events. The key questions to be answered regarding neutral hydrogen structures in the circumgalactic environment are thus:

- What is the population of HI clouds around galaxies, and how does this link to the 'missing subhalos' problem?
- Do we see evidence in the local universe for cold-mode accretion of hydrogen onto galaxies?

Group and field environment

The Arecibo Legacy Fast Arecibo L-band Feed Array (ALFALFA) survey has found a population of ultra-compact HVCs that could not be easily associated with the known population of HVCs around the Milky Way and had properties suggestive of their being very low mass galaxies in the Local Volume (Giovanelli et al. 2010; Adams et al. 2013). If extragalactic, these clouds would have HI masses of 10^5–10^6 $M_\odot$ and their counterparts would thus likely have escaped detection in existing HI surveys of nearby groups (Giovanelli et al. 2010).

Very faint optical counterparts have been found for some of the nearby sources found by ALFALFA, in particular Leo P (Skillman et al. 2013) and AGC 198691 (Hirschauer et al. 2016) have been found to be extremely low metallicities dwarf galaxies (XMDs). These represent 40% of the known XMDs in the local universe. While the other three (SBS 0335–052W, I Zw 18, and DDO 68) all have extreme star-formation rates, making them much more luminous (and thus easy to discover) than would be expected from the normal luminosity-metallicity relationship, the two ALFALFA XMDs are much closer to this relationship (Hirschauer et al. 2016). If there were other bright XMDs in the local universe, they should have been discovered in optical surveys, but the potential exists for many more faint XMDs similar to the ALFALFA dwarfs to be found by future HI surveys.

The study of extremely low metallicity galaxies has a significance well beyond the local universe, as the galaxies being studied at high-z by ALMA (and in the future by JWST) have metallicities well below those normal at z=0. Studying the local XMDs uncovered by HI surveys may give vital clues as to the nature of these high-z galaxies.

In addition to the XMD galaxies, the ALFALFA cloud AGC 198606 has been imaged with the WSRT (Adams et al. 2015) and gives the appearance of being a gas-bearing mini-halo. A very faint optical counterpart has been identified (Janesh et al. 2015) that would place this in the local group at 373–393 kpc. The AGC 249525 cloud also has the appearance of being a dwarf galaxy in resolved HI observations (Adams et al. 2016) and an optical counterpart has been identified that places it near the edge of the Local Group at 1.64±0.45 Mpc (Janesh et al. 2017). The Coma P cloud, at a distance of 5.50 ± 0.28 Mpc, has a more complicated HI morphology but is again an extremely low surface brightness galaxy ($\mu_{g'}$ = 26.4±0.1 mag arcsec^{-2}) and would have escaped detection in virtually all optical surveys (Ball et al. 2018). The metallicities of these sources are currently unknown, but are again likely to be very low.

All of these demonstrate that the ALFALFA '(almost) dark' clouds could be the low mass halos predicted to exist by simulations in numbers considerably higher than are found in galaxy groups such as the Local Group. If such halos have very inefficient star formation this could leave most of their detectable baryons in the form of HI – giving sources similar to the ALFALFA objects that can be uncovered in the next decade by sensitive HI surveys of local groups (c.f. ASAP 2011; Giovanelli 2010).

Determining that a population of sources in a nearby group is distinct from the HVCs around a galaxy is much simpler than distinguishing between dark objects in the local volume, Local Group or around the Milky Way as the distance is well known without the need to identify an optical counterpart with a measurable red giant branch; a survey of nearby groups down to 10^5 $M_{\odot}$ and with sensitivity to low column-density gas would therefore almost certainly discover a population of dark HI clouds, if the ultra-compact HVCs seen by ALFALFA are extragalactic, or would determine that the ALFALFA clouds are probably a new Galactic population. It would also be very likely to discover further almost-dark galaxies occupying very low mass halos, probably with very low metallicities, in numbers allowing for a statistical analysis of their properties. As it would be targeting galaxy groups in the local universe, such a survey would not need very high spatial resolution (and high resolution would make the identification of sources more complicated), although resolved HI follow-up observations (along with multi-wavelength observations if optical counterparts are identified) may be necessary to fully determine the properties of the sources found. The survey would also be able to detect any large and/or extended HI structures in the groups targeted resulting (probably) from tidal interactions, such as those seen by Oosterloo et al. (2018) and Madrid et al. (2018).

Such a survey would allow two interlinked questions to be addressed:

- What are the properties of the lowest mass halos in the local universe, and how do ΛCDM simulations relate to the observable, baryonic universe?
- What are the properties of the lowest metallicity galaxies in the local universe?

Cluster environment

Cluster environments contain a far higher proportion of dwarf galaxies that groups, and thus do not appear to suffer from the 'missing galaxies' problem. Nonetheless, they do still contain dark structures that are detected by HI surveys. While there were serendipitous discoveries prior to the era of blind HI surveys, such as HI 1225+01 (Giovanelli & Haynes 1989), many more such objects have been uncovered in recent years. These objects often have lower HI column densities than are generally found in galaxies, such that the deeper Arecibo Galaxy Environment Survey (AGES) has found half of the dark sources known in the Virgo cluster despite covering only around 20% of the cluster compared to the 100% coverage of ALFALFA (Taylor et al. 2012; 2013). Column-density sensitivity is thus key for surveying this environment.

Recent work in the Virgo cluster with AGES (Taylor et al. 2019) has shown that, at the low column densities reached, possible ram-pressure tails can be seen on many more galaxies than previously, while the new Widefield Arecibo Virgo Extragalactic Survey (WAVES; Minchin et al. 2019) has revealed a much longer tail than seen before on NGC 4522 – giving new clues as to the motion of this galaxy through the cluster and showing that the fading of the tail is consistent with geometric dilution – and has found new structures (Figure 2) in a dark HI cloud complex (the 'Kent complex') originally discovered by ALFALFA (Kent et al. 2007; 2009).

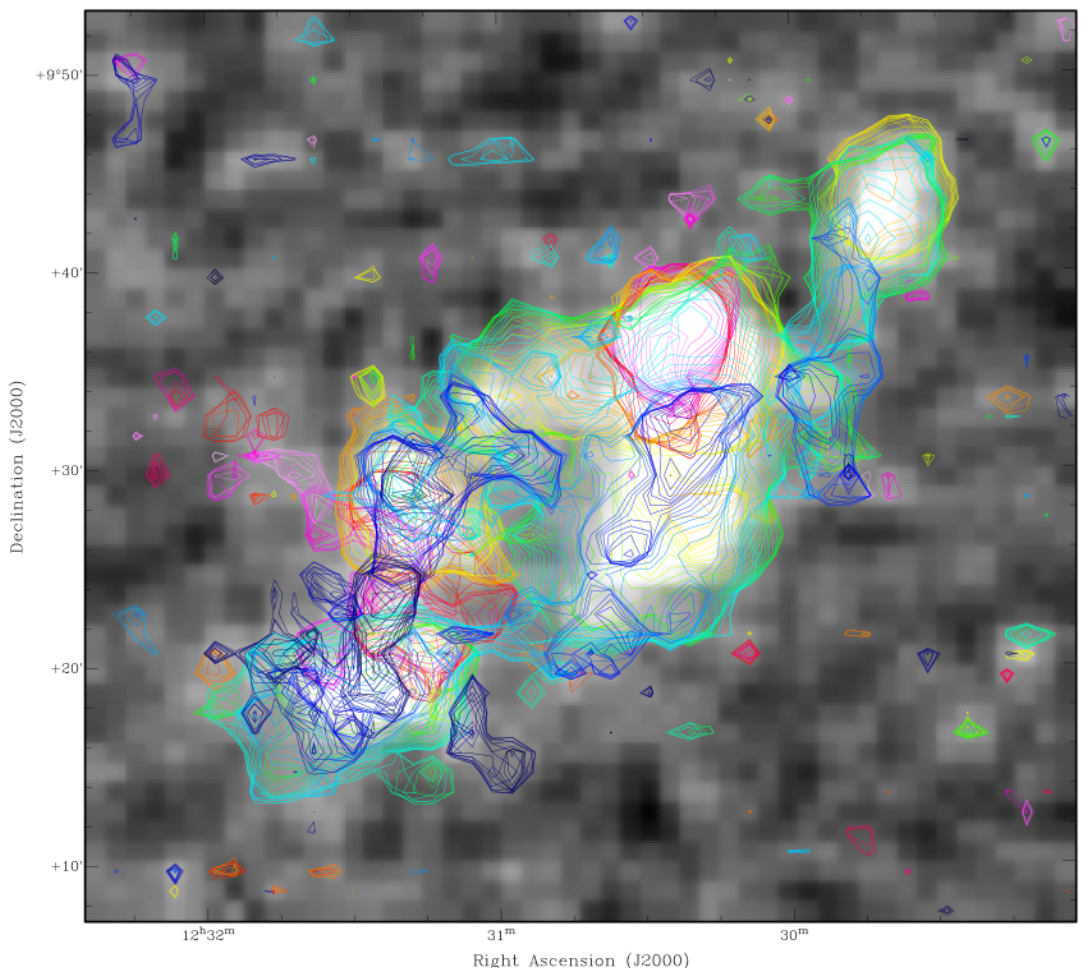

Figure 2. Renzogram overlaid on moment 0 map of the Kent complex in the Virgo cluster (from Minchin et al. 2019; Fig. 3)

Clusters also contain numerous compact clouds (Taylor et al. 2012), some of which have remarkably large velocity widths. The origin of these clouds is not understood – the formation of isolated, compact clouds with velocity widths > 100 km/s is highly unlikely in tidal interactions compared to the formation of clouds with velocity widths < 50 km/s (Taylor et al. 2017) or via harassment of long streams (Taylor et al. 2016), and they cannot survive in pressure equilibrium with the intracluster medium for extended periods (Taylor et al. 2018).

Future surveys of Virgo and other clusters, sensitive to low column-density HI, will discover more dark structures: isolated compact clouds, free-floating gas complexes and tails attached to galaxies. These will give us vital information on how the gas in removed from galaxies – a driver of morphological transformation in the cluster environment – including the balance between tidal tails, such as the VIRGOHI 21 stream attached to NGC 4254 (Minchin et al. 2005; 2007; Haynes et al. 2007), and ram pressure tails such as that seen on NGC 4522 (Kenney et al. 2004; Chung et al. 2007; Minchin et al. 2019). They will also allow us to investigate the fate of that gas once it is removed from the galaxies, and how apparently long-lived structures such as HI 1225+01 and the Kent complex, as well as the compact clouds, are created and survive. The questions to be answered here are:

- How is the gas removed from galaxies in the cluster environment?
- What is the origin of the isolated gas clouds and complexes seen in clusters?
- What is the fate of the gas removed from galaxies in the cluster environment?

Commensality

The frequency range used for HI surveys is also that used for pulsar surveys. As a result, commensal surveys, where data is taken for both HI and pulsar science simultaneously, can be realized with careful survey design, giving a massive saving in telescope time. This has led to important discoveries such as the first repeating fast radio burst, found in pulsar data recorded alongside an HI survey at Arecibo (Spitler et al. 2016).

Key advances

Enabling the surveys proposed here will require various advances in instrumentation to drive advances in survey speeds. The group and cluster environments can be covered efficiently with phased array feeds on single-dish radio telescopes (which will always have higher column-density sensitivity than interferometers), and follow-up HI observations could be made with current instrumentation but would be more efficient with interferometers that had a high sensitivity to low column-density gas (i.e. designed with a dense ‘core’ having a high filling factor). Surveying the circumgalactic environment outside of the Local Group will require interferometers with high sensitivity to low column-density gas. Continued investment in simulations will also be required to properly interpret the results of all of the surveys.

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