Compact High Velocity Clouds

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Abstract.
We summarize the observed properties of the CHVC population, which provide strong evidence for source distances in the range 200–1000 kpc. At these distances, the population corresponds to strongly dark-matter dominated sub-dwarf galaxies still accreting onto the more massive Local Group systems. Recent searches for faint associated stellar populations have revealed red-giant candidates for which follow-up spectroscopy is scheduled. A sensitive H\textsc{i} survey for CHVC counterparts in the NGC 628 galaxy group has allowed tentative detection of 40 candidates, for which confirming observations have been approved. Many open issues should be resolved by observational programs within the coming years.

1. Introduction

The H\textsc{i} High Velocity Cloud (HVC) phenomenon has been studied for some three decades, but it is only with the sensitive, all-sky imaging of the LDS (Hartman & Burton 1997) in the North and HIPASS (Staveley-Smith et al 1999) in the South, that some important aspects of the phenomenon are becoming apparent. Even a casual inspection of these data reveal a striking dichotomy in the types of emission features present. The vast majority of the emission flux is associated with diffuse filamentary complexes extending over 10’s of degrees, of which the Magellanic Stream (Putman 2000) is a prime example. A much smaller total flux is associated with a population of compact, high-contrast features which are isolated from any other H\textsc{i} emission features both spatially and in velocity (the CHVCs). My attention was first drawn to this second object class, while using the LDS data to assess possible Galactic foreground confusion in the directions of nearby galaxy groups in the fall of 1997. I was surprised to see high contrast peaks of uncataloged high-velocity H\textsc{i} which were indistinguishable in the LDS data from the H\textsc{i} signatures of nearby dwarf galaxies. This was so intriguing to me that I set about making a catalog of such objects based on the LDS data (covering $\delta = -30\text{--}90^\circ$). Together with Butler Burton, follow-up observations of all candidate sources were obtained and a list of 65 confirmed objects were published (Braun & Burton 1999).
2. CHVC Properties

In addition to having a distinctive, compact morphology (average FWHM of 50±25 arcmin) the CHVCs also proved to have a very systematic spatial and kinematic distribution on the sky. A global search over all direction cosines for the reference system that minimized the velocity dispersion of the population, returned the Local Group Standard of Rest (LGSR) with high significance. In the LGSR, the CHVC population has a velocity dispersion of only 70 km s\(^{-1}\), in contrast to 95 km s\(^{-1}\) measured in the Galactic Standard of Rest (GSR). But rather than being at rest in the LGSR frame, the entire system is infalling by about 100 km s\(^{-1}\) toward the Local Group barycenter. These distinctive kinematic properties of the CHVC population were the first indication that they might reside at substantial distances, and were not merely a local ISM or Galactic phenomenon.

2.1. Velocity Gradients and Multi-Core Systems

Further indications for a substantial distance to these objects have emerged from a program of high resolution H\(_i\) synthesis imaging with the WSRT (Braun & Burton 2000) and in total power with Arecibo (Burton, Braun & Chengalur 2000). The general picture which has emerged is that of one or more compact cores (of 1–20 arcmin extent) embedded in a common diffuse halo. On average about 40% of the H\(_i\) line flux is due to the compact cores, although this varies enormously; ranging from <1% for the lowest flux objects (less than about 50 Jy-km s\(^{-1}\)) to about 50% for brighter systems (100–300 Jy-km s\(^{-1}\)). Many of the compact cores display velocity gradients (of 10–30 km s\(^{-1}\) amplitude) along the long dimension of an approximately elliptical extent. For multi-core objects, each core has its own distinct kinematic axis, which is uncorrelated with that of other cores in the same object (and can be perpendicular as often as parallel). It is difficult to envision an external mechanism (such as tidal shear for example) for imparting vastly different kinematic axes to the various cores of a single object. Resolved detection of the diffuse halos with deep Arecibo imaging has shown that the halos do not participate in the same velocity gradients of the cores, but are more nearly stationary at the systemic velocity of the object and always have the 22+ km s\(^{-1}\) FWHM linewidth of an 8000+ K gas. This implies that either (1) the velocity gradients of the cores have an internal (like self-gravity) rather than external origin or (2) the objects are sufficiently long-lived that the halos can become thermalized (and so erase their original kinematics). In any case, the thermalization timescale for a 50 arcmin diffuse halo is \(\tau_t \sim D_{kpc} \text{ Myr}\), at a distance of \(D_{kpc}\) in kpc.

The most extreme multi-core CHVC yet studied (CHVC115+13−275) has some 10 major core components spanning about 30 arcmin on the sky with centroid velocities distributed over no less than 70 km s\(^{-1}\)! This object, and others like it, either have an extremely short dynamical lifetime (\(\tau_d < 0.1D_{kpc} \text{ Myr}\)) or are bound by a large amount of dark matter. From the very narrow H\(_i\) linewidths seen in the cores we know that internal conditions are appropriate for maintaining H\(_i\) at about 100 K, which requires that the product, \(n_Ht > 1 \text{ cm}^{-3}\text{Myr}\) (Draine 1978).
While self-gravity could account for all of these facts in a natural way: (1) the cool H\textsc{i} cores by the enhanced internal pressure of a self-gravitating system, (2) the local velocity gradients as rotation in dark-matter-dominated mini-halos, (3) the binding of multi-core objects by a massive dark halo; it is not clear which alternative scenario might work. The projected velocity fields of the best-resolved cores can be well-modeled by a slowly rising rotation curve, leveling off at 8 arcmin radius to a velocity of 15–20 km s\(^{-1}\). The implied total masses in these individual cores is about \(D_{700} \times 10^8 M_\odot\), while for the high linewidth multi-core systems it is nearer \(D_{700} \times 10^9 M_\odot\); in terms of an assumed distance \(D_{700}\) normalized to 700 kpc. Even at these rather substantial assumed distances, the dark-to-visible mass ratios are quite high with individual cores ranging from \(\Gamma = 10–40/D_{700}\), while for the multi-core systems \(\Gamma \sim 50/D_{700}\).

2.2. Opaque H\textsc{i} Clumps

The objects with the narrowest H\textsc{i} emission lines have also proven particularly interesting. Compact clumps of opaque H\textsc{i} (with 90 arcsec FWHM) have been observed within the cores of at least one source to date (CHVC 125+41–207). Such clumps have H\textsc{i} brightness temperatures of 75 K, together with FWHM linewidths of less than about 2 km s\(^{-1}\). These values allow a reliable determination of the kinetic temperature (85 K) and opacity (\(\tau \sim 2\)) as well as an upper limit on turbulent contributions to the internal linewidth (<1 km s\(^{-1}\)). Since we have measured an angular size and excess column density for the clumps we can estimate the distance from \(D = dN_H/(n_H \theta)\), assuming crude spherical symmetry, if we have an estimate of the H\textsc{i} volume density, \(n_H\).

We can perhaps demonstrate this method best by using M31 as an example. The excess column density, \(dN_H = 5 \pm 1 \times 10^{21} \text{cm}^{-2}\), and angular size, \(\theta = 60 \pm 20\) arcsec, of H\textsc{i} clumps in the North-East half of M31 can be estimated from Fig. 5 of Braun & Walterbos (1992). The H\textsc{i} kinetic temperature, \(T_k = 175 \pm 25\) K, and estimated thermal pressure, \(P/k = 1500 \pm 500\) cm \(^{-3}\)K, of the M31 mid-disk are tabulated in Table 4 of the same reference. The implied volume density, \(n_H = 9 \pm 3 \text{ cm}^{-3}\), leads to the distance estimate: \(D_{M31} = 670 \pm 220\) kpc. While rather crude, this approach gives a plausible value for the distance to M31. For CHVC125+41–207, we have an excess column density, \(dN_H = 1.0 \pm 0.2 \times 10^{21} \text{cm}^{-2}\), and angular size, \(\theta = 90 \pm 15\) arcsec, of the H\textsc{i} clumps for which \(T_k = 85 \pm 10\) K. Although the thermal pressure, \(P/k\), in the solar neighborhood is about 2000 cm \(^{-3}\)K, it is expected to decline rapidly with distance from the Galactic plane (eg. Wolfire et al. 1995) such that beyond about 10 kpc we should encounter values, \(P/k = 150 \pm 50\) cm \(^{-3}\)K, leading to an estimated volume density, \(n_H = 2 \pm 1 \text{ cm}^{-3}\). In fact, as described in Braun & Burton (2000), an H\textsc{i} temperature equilibrium calculation was performed by Wolfire et al. (2000) assuming a Local Group radiation field and a metallicity and dust-to-gas ratio of 10% Solar which allowed exactly these pressure and density estimates to be made for this object. The resulting distance estimate is, \(D_{C125} = 600 \pm 300\) kpc.

2.3. Halo Edge Profiles

Another result of the Arecibo imaging of CHVCs reported in Burton, Braun & Chengalur (2000) was the detection of approximately exponential edge profiles
of the diffuse halos between column densities of about $10^{19}$ down to the limiting sensitivity ($1\sigma$ over 70 km s$^{-1}$) of $2 \times 10^{17}$ cm$^{-2}$. (BTW, these are probably some of the deepest H I emission measurements of resolved objects yet obtained.) The edge profiles are well-fit by the sky-plane projection of a 3-D spherical exponential in H I volume density, $n_H(r) = n_0 e^{-r/h}$, in terms of the radial distance, $r$, and exponential scale length, $h$, yielding $N_H(r) = 2hn_0(r/h)K_1(r/h)$, where $K_1$ is the modified Bessel function of order 1. Fitting this form to the observed edge profiles allows accurate assessment of both the central column density of the warm halo, $N_H(0)$, and the scale length, $h$, in the plane of the sky. As before, with any reasonable estimate of the thermal pressure, it becomes possible to determine the source distance assuming crude spherical symmetry. Assuming a pressure in the diffuse CHVC halos, $P/k \sim 100$ cm$^{-3}$K, results in distance estimates which vary between 150–1100 kpc for the ten CHVCs with measured edge profiles.

2.4. Do LMC Distances Work?

What about placing the CHVCs at the distance of the LMC/SMC? All existing estimates of the thermal pressure at these distances lie at or below about $P_{th}/k \sim 100$ cm$^{-3}$K. To this could be added the ram pressure $P_{ram} \sim \rho v^2/2$ of passage through the hot halo of the Galaxy. Assuming a typical relative velocity of 100 km s$^{-1}$, and a Galactic halo temperature of $10^6$K, gives $P_{ram} = 0.8P_{th}$, implying a significant, but not dominant contribution to the total pressure. In order to account for the H I column densities and angular sizes of both the opaque clumps seen in CHVC125+41−207 as well as the diffuse halos of the ten CHVCs observed with Arecibo, we would require some additional source of pressure to yield 3–20 times higher values. It is not clear where this might come from. At a distance of about 50 kpc, the thermalization timescale of the diffuse CHVC halos is 50 Myr, while the dynamical lifetime of multi-core CHVCs like CHVC115+13−275 is only 5 Myr. So, on the one hand, the absence of velocity...
gradients in the diffuse halos demands a long source lifetime, while on the other, the sources are too short-lived for the halos to be thermalized. This scenario is very difficult to reconcile with the observed CHVC properties.

3. Current Work on CHVCs

Although a large number of the CHVC attributes suggest Local Group distances, the various distance determinations outlined above remain indirect. Essentially, a self-consistent scenario has emerged, in which many physical and kinematic properties of the CHVCs can be understood if they are self-gravitating, dark-matter-dominated systems. It is very appealing to associate them with the low-mass “building-blocks” of galaxy formation (Blitz et al. 1999), which high resolution numerical simulations suggest should still be found in large numbers in the appropriate environments (Klypin et al. 1999, Moore et al. 1999). If this connection can be demonstrated convincingly we would have the opportunity to gain important insights into a wide range of fundamental problems in astrophysics, through the study of these cosmological fossils in our own “backyard”. However, demonstrating consistency does not constitute a proof of the conjecture. We are pursuing several different lines of research to clarify the nature of these objects.

3.1. All-Sky CHVC Population

Vincent de Heij (as part of his PhD work in Leiden) working together with Mary Putman, has just completed cataloging the population of Southern hemisphere CHVCs using the HIPASS data (Putman, De Heij et al. 2000). The Southern hemisphere data is particularly important in constraining the kinematics of the population, since this is where it extends to the highest positive velocities in the LSR reference frame. It is also special in the sense that both the nearest external galaxies, the Magellanic Clouds, as well as the nearest external galaxy group, the Sculptor Group, are located there. Just as was seen previously in the LDS data North of $\delta = -30^\circ$, there is a clear distinction in the HIPASS data between the extended filamentary complexes which make up the bulk of peculiar velocity H I emission and the compact, isolated CHVCs, which have the H I appearance of nearby dwarf galaxies. About 100 well-defined CHVCs were cataloged below $\delta = 0^\circ$ in the HIPASS data. A new analysis of the spatial and kinematic properties of the all-sky CHVC population will be carried out in the coming months. High resolution H I imaging data has also been acquired with the WSRT for eight additional objects. These targets were chosen on the basis of high brightness temperatures in the LDS data, in the hope of detecting more opaque clumps of the type seen in CHVC125+41−207.

3.2. Stars in CHVCs

An unambiguous distance determination for the CHVCs would follow from direct detection of an associated stellar population. A high surface brightness stellar disk can already be ruled out for all of the CHVCs outside of the Galactic plane Zone of Avoidance. The constraints on low surface brightness populations are not yet very strong, especially since they would be highly resolved into individual stars at distances of 200–1000 kpc, which would be difficult to distinguish
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from the dense Galactic foreground. If young, high mass stars were present, then these should give rise to prominent \textsc{H} \textsc{ii} regions. Together with René Walterbos (NMSU), we have begun a program of narrow-band Hα imaging of CHVCs with the APO 1-m; so far without detections in the first three fields imaged. An older stellar population could be traced by its most luminous and populous component, namely the red-giant branch. Deep searches for associated red-giants have been carried out in the spring and summer of 2000 using the Mosaic cameras on the KPNO 4-m and CTIO 4-m together with Eva Grebel and Daniel Harbeck (MPIA) and the LCO 2.5-m together with Carme Gallart (Yale/Chile) and Steve Majewski (UVa). Besides several broad-band colors, the DDO51 filter, centered on the MgH absorption feature at 5100 Å, was used to allow reliable discrimination of the many foreground white-dwarfs from faint background objects. While still only partially analyzed, these data do suggest a sparse population of candidate stars in several objects with the colors of red-giants and luminosities consistent with a 700 kpc distance. However, at these faint brightnesses, there is the possibility of confusion by background galaxies at red-shifts of a few tenths which resemble the sought for red-giant population when viewed with typical ground-based angular resolutions of about 1 arcsec. Two additional observing programs together with Eva Grebel and Kem Cook (LLNL) have already been allocated for fall 2000 to clarify this issue; namely high resolution imaging with the VLT, and multi-object spectroscopy of candidate stars with Keck. Stay tuned . . .

3.3. Exo-CHVCs

Another way to circumvent the difficulties of distance determination of the Local Group CHVCs is to detect CHVC counterparts in external groups of galaxies. However, the low mass end (below $M_{HI} \sim 10^8 \, M_\odot$) of the \textsc{H} \textsc{i} mass function (HIMF) is still a topic of very active current research. Only small numbers of low mass objects have been detected to date in blind, large area surveys: eg. 4 out of 66 in the AHISS (Zwaan et al. 1997), 4 out of 79 in the “Areco Slice” (Spitzak & Schneider 1998), 3 out of 263 in the HIPASS (Kilborn et al. 1999) and 7 out of 265 in the ADBS (Rosenberg & Schneider 2000). Consequently, there are substantial uncertainties in the space densities at low \textsc{H} \textsc{i} mass due to small number statistics.

Targeted searches for uncataloged objects in specific environments are beginning to supplement the blind surveys. Banks et al. (1999) detect 17 out of 27 objects with $M_{HI} < 10^8 \, M_\odot$ in the Cen A group of galaxies using HIPASS data. Verheijen et al. (2000) detect comparable numbers of objects in the Ursa Major cluster in a recent VLA survey.

Comparison of the HIMFs derived by the various authors is beginning to show what might be substantial differences in the statistics of the low mass populations seen in different environments. Within the Ursa Major cluster, for example, the low mass HIMF is flat or even declining towards lower masses. In the poorer, but still relatively rich, environment of the Cen A group there appears to be a significant increase to lower masses. The detected space density in the lowest measured bin (11 objects centered at $2 \times 10^7 \, M_\odot$) is twice that seen in the next lowest bin (6 objects centered at $6 \times 10^7 \, M_\odot$). A similar, but still low significance, upturn is apparent in the population of “field” galaxies
sampled by both the Southern sky HIPASS data and the combined AHISS and Arecibo Slice data reported by Schneider et al. (1998).

Detection of rather different HIMFs in different environments is not in itself a surprising result. The interaction, merger and stripping rates of low mass systems must depend sensitively on the richness of their environment. Optical luminosity functions have not demonstrated a strong dependence of shape with environment (eg. de Propris et al. 1995; Loveday 1997; Marzke et al. 1998) but what they all seem to share is a strong upturn in the space density of low luminosity systems below $M_B \sim -15$. Given the much larger interaction cross-section of diffuse gas over that of stars, we should expect dramatic differences in the low mass end of the HIMF, even if the “primordial” HIMF were the same everywhere.

The latest HI surveys have begun to reveal a rather interesting population of sources at the very low mass end in poor environments. The previously uncataloged HI detections in the Cen A group (Banks et al. 1999) all have very low luminosity ($M_B \sim -11$), low surface brightness $<\mu> \sim 26$ mag arcsec$^{-2}$ optical counterparts. In the case of the ADBS (Rosenberg & Schneider 2000) fully 22 of 81 previously uncataloged objects have no clear optical counterpart down to the limiting magnitude of the POSS (about 25 mag arcsec$^{-2}$). Of these 22 objects, 11 have substantial extinction ($A_V > 2$ mag) and therefore do not provide strong limits, but 5 have negligible extinction ($A_V < 0.3$ mag) and are thus quite interesting. The most extreme object in this category may be the possible Cen A group member HIPASS J1712$-64$ (Kilborn et al. 2000) for which an upper limit of $\mu_B = 27$ mag arcsec$^{-2}$ is associated with an HI mass of $1.7 \times 10^7 M_\odot$. Are we perhaps encountering the tip of an iceberg of very low mass systems with only a faint (or even no) population of associated stars?

Together with Butler Burton, we have undertaken an attempt to probe the extreme low mass end of the HIMF in a poor environment by carrying out a deep survey of the NGC 628 galaxy group. Nineteen sparse pointings, distributed over a region of about 1 Mpc (or 5 degrees) in diameter, were each observed with a 12 hour integration using the recently upgraded Westerbork array. The $5\sigma$ HI mass sensitivity at each field center was $2 \times 10^6 M_\odot$ over the minimum expected linewidth of 32 km s$^{-1}$ FWHM (although the velocity resolution was 5 km s$^{-1}$). Since the pointings were sparsely distributed, they only overlap at the 5% level of the circular Gaussian primary beam with 2100 arcsec FWHM. At these “cracks” in the hexagonal pointing pattern, the $5\sigma$ mass sensitivity is degraded to $4 \times 10^7 M_\odot$ over 32 km s$^{-1}$. Applying a significance criterion of 0.5 random noise detections per data cube (varying between 5.5 and 5.0 times $\sigma$ depending on the degree of velocity smoothing, and hence the number of independent pixels) resulted in a list of 48 tentative detections in the complete survey. Of these, only 7 correspond to previously cataloged galaxies. One of the remaining 41 candidates has an obvious optical counterpart in the POSS data, while three more have faint wisps in the POSS that may be low surface brightness optical counterparts (with peak $\mu_R \sim 25$ mag arcsec$^{-2}$). The remaining 37 candidates have no optical counterparts down to this surface brightness limit. Given the noise statistics we expect about 10 of our candidates to be random noise peaks, which is also the number of “negative sources” found with the same
criteria in the survey data. Confirming observations of our low mass candidates with the Arecibo telescope have been approved for fall 2000.

4. Conclusions

These are very interesting times for high velocity H\textsc{i} cloud research. Substantial progress has been made in determining the physical properties of these objects. The weight of current evidence seems to favor a large mean distance for the compact isolated objects, the CHVCs. More insights and perhaps definitive evidence should follow within the next year or two from a number of ongoing programs.

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