Searching for stars in compact high-velocity clouds – II

U. Hopp,1,2⋆ R. E. Schulte-Ladbeck3 and J. Kerp4

1Universitäts-Sternwarte München, Scheinerstr. 1, D-81679 München, Germany
2Max–Planck–Institut für Extraterrestrische Physik, Giessenbachstr., D-85748 Garching, Germany
3Department of Physics & Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA
4Radioastronomisches Institut der Universität Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany

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ABSTRACT

We address the hypothesis that high-velocity clouds correspond to the ‘missing’ dwarf galaxies of the Local Group predicted by cosmological simulations. To this end, we present optical and near-infrared photometry of five additional high-velocity clouds, one of which produces Lyman series absorption on the sight line towards the quasar Ton S210, with sufficient resolution and sensitivity to enable the detection of an associated stellar content. We do not detect significant stellar populations intrinsic to any of the five clouds. In combination with the results from our Paper I, which had yielded non-detections of stellar content in another five cases, we find that there is a 50 per cent chance of getting a null result in 10 trials if fewer than 7 per cent of all high-velocity clouds contain stars. We conclude that the population of high-velocity clouds is an unlikely repository for the ‘missing’ dwarfs of the Local Group.

Key words: ISM: clouds – Galaxy: formation – Galaxy: halo – Local Group.

1 INTRODUCTION

Simulations of structure formation predict the existence of hundreds of small satellite haloes in large parent haloes (Klypin et al. 1999; Moore et al. 1999). Accordingly, and unless low-mass satellite haloes are free of gas and stars, a structure such as the Local Group should contain several hundred dwarf galaxies. The actually observed number is an order of magnitude smaller (Mateo 1998). This has given rise to the ‘missing’ dwarfs problem of cosmological simulations.

The Local Group dwarfs may still be there but may have been overlooked by previous observations. This is the basic premise of our work. Specifically, Blitz et al. (1999) proposed that the ‘missing’ dwarfs could be associated with high-velocity clouds (HVCs). HVCs are parcels of gas with extremely high radial velocities that are inconsistent with Galactic rotation models. Unfortunately, it has proven very difficult to determine distances for HVCs (e.g. Wakker & van Woerden 1997; Braun 2001; Putman 2006). In the Blitz et al. hypothesis HVCs are extragalactic with a mean characteristic distance of about 1 Mpc, rather than clouds in the Galactic halo. They are considered to be leftover building blocks that are infalling into the Local Group.

The suggestion that HVCs could be the ‘missing’ dwarf galaxies of the Local Groups has spurred several searches for their stellar content. Searches for stars in HVCs have either looked for overdensities above Galactic foreground in the stellar distributions towards HVCs, or, if data of sufficient resolution were available in two or more filters, they have employed colour–magnitude diagrams (CMD) in an attempt to measure distances from stellar population ‘standard candles’.

High-surface-brightness galaxy counterparts to HVCs were quickly ruled out (Braun & Burton 1999), Simon & Blitz (2002) inspected digitized Palomar Sky Survey (POSS) plates for 264 northern HVCs with a spatial filtering method. The surface brightness limits reached by their analysis (e.g. 26 mag arcsec$^{-2}$ in V) would have recovered all known Local Group galaxies with the exception of four nearby and extended dwarf Spheroidal galaxies. Similarly, Sloan Digital Sky Survey data of 13 HVCs (including one compact HVC, hereafter CHVC) have not revealed any stellar overdensities which could be attributed to an intrinsic stellar content (Willman et al. 2002).

Optical CMD searches for stars in HVCs have been described in Braun (2001), Davies et al. (2002) and Siegel et al. (2005), while a near-infrared CMD search toward one cloud has been discussed in Simon et al. (2006). All of these works, further discussed in Section 4, indicate that there is no resolved stellar content in HVCs.

Hopp, Schulte-Ladbeck & Kerp (2003, hereafter Paper I) combined deep optical and archival near-infrared photometry of stellar distributions toward four CHVCs and one HVC. This observational approach allowed us to conduct a systematic search for stars (a) within a field of view that was much smaller than the size of the H1 distributions but with a sensitivity that reached twice the characteristic distance of 1 Mpc proposed by Blitz et al. (1999), and (b) within a field of view that covered the H1 extent of the clouds but with a sensitivity that reached only half of the characteristic distance at best. We showed that our technique is very sensitive to low-surface-brightness populations, reaching a V-band surface brightness of about 26.5 mag arcsec$^{-2}$.
Table 1. (Compact) HVCs observed with VLT/FORS. \( N \) stars is the number of point sources detected in both \( V \) and \( I \).

| Identifier | RA (h:m:s) | Dec. (°:′:″) | \( A_V \) (m) | \( A_K \) (m) | \( N \) stars |
|------------|------------|--------------|--------------|--------------|--------------|
| CHVC 039.4−73.6−165 | 23:39:48 | −24:08:00 | 0.061 | 0.007 | 165 |
| CHVC 224.0−83.4−197 | 01:20:42 | −28:12:00 | 0.052 | 0.006 | 198 |
| HVC 229−74−168 | 02:02:46 | −30:11:00 | 0.066 | 0.007 | 190 |
| CHVC 225.1−42.5+175 | 04:26:00 | −26:31:00 | 0.145 | 0.016 | 234 |
| HVC 225−42+190 | 04:29:48 | −26:00:00 | 0.131 | 0.014 | 503 |

The optical data were gathered in continuation of our service observing project at the European Southern Observatory’s (ESO) Very Large Telescope (VLT) facility. The data were collected in fall of 2002 and summer of 2003. Our second observing sample was approved for an additional five targets. The target list is presented in Table 1. The targets were selected from the catalogues of Braun & Burton (1999) and Putman et al. (2002). The objects from the Putman et al. paper are all classed CHVC in that catalogue. Note that Braun & Burton (1999) select as a CHVC a cloud whose integrated \( H_I \) emission at the half power contour has an area of less than 4 deg\(^2\). It should be noted that the area of the optical detector used in this work had an area of only 50 arcmin\(^2\) (or 0.01 deg\(^2\)) while the area of the CHVCs covered an area of about 3 deg\(^2\). The pointings/extractions were based on the Two Micron All Sky Survey (2MASS) extended source catalogues, which contains stars is less than 13 per cent. Here we present an extension of our work from Paper I to an additional five objects, and discuss the statistical implications of the results.

2 DATA

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The 2MASS project is a collaboration between the University of Massachusetts and the Infrared Processing and Analysis Center (JPL/Caltech). Funding is provided primarily by NASA and the NSF.
the second incremental data release of the 2MASS point-source catalogue in Paper I, here we use the final 2MASS archive. The 2MASS data were extracted via the Infrared Processing and Analysis Center (IPAC) WWW site. As in Paper I, we culled point sources within a 1° radius of the positions listed in Table 1. The 2MASS fields thus cover most of the H1 distributions of the (C)HVCs.

We produced near-infrared position plots and CMDs. The position plots and CMDs for the new targets differ from those of the previously studied ones only in that they contain fewer foreground stars due to higher Galactic latitudes. We provide one sample position plot (Fig. 2), and one sample [J − Ks, Ks] CMD (Fig. 3), choosing again CHVC 224.0−83.4−197. At the time we wrote Paper I, there were no 2MASS data available as yet for one of the sample objects, HIPASS J1712−64. Data for this HVC were extracted from the final archive, and inspected along with those of the new targets. The position plots and near-infrared CMDs of HIPASS J1712−64 are qualitatively similar to those of other (C)HVCs at comparable Galactic latitudes.

3 RESULTS

The (C)HVCs we targeted are located at high Galactic latitudes. Therefore, the contribution by red Galactic foreground stars to the data is small. This has benefits in particular for distinguishing late-type stars, such as red giant branch (RGB) stars or asymptotic giant branch (AGB) stars, intrinsic to the (C)HVCs, from Galactic foreground stars. Indeed, the number of sources detected in the optical, N stars from Table 1, for example, is factors of 2 to 5 smaller compared to what we saw in Paper I. Given that the data were obtained with the same instrumentation and under similar conditions, we attribute this drop in N stars to the fact that the Galactic foreground for the targets observed here is factors of 2 to 5 smaller than it was for our first sample. A model of the stellar distribution perpendicular to the galactic disk follows an exponential drop in stellar density (e.g. Kuijken & Gilmore 1989), which can be well approximated by a plan-parallel description for the earth-bound observer. Thus, to first order, the surface density of disk stars should vary as \( \cos(b) \) with \( b \) the Galactic latitudes (here between \( \approx 30^\circ \) and \( \approx 75^\circ \)). This implies variations of a factor of \( \approx 3.3 \) in good agreement with our observations. A more realistic approach is given by the so-called Besançon models of Robin et al. (2003). We used the web page calculator of these models to verify that the trend in number counts with galactic latitude shown by these models agree pretty well with our I-band observations.

The \([ V − I, I ]\) CMDs of the (C)HVCs in the new sample are qualitatively similar to what we observed in Paper I. This can be seen by comparing Fig. 1 in this paper to fig. 1 in Hopp et al. (2003). There is a fan-shaped distribution of stars bound by the detection limits and by \( V − I \approx 1 \); and the number of stars increases toward fainter magnitudes. Most significantly, the CMDs of the (C)HVCs are quite different from those of known Local Group dwarf galaxies: we notice neither a young, blue plume nor an old red, plume of stars extending over about 4 mag in \( I \). The tip of the red giant branch (TRGB) for the full range of stellar metallicities. It is a well-calibrated distance indicator (Lee, Freedman & Madore 1993); and, at a distance of 1 Mpc, it would appear at \( I \approx 21 \). A TRGB for the full range of stellar metallicities would have been detected to \( I \) magnitudes of at least 22.5, or to a distance of up to 2 Mpc, in the (C)HVCs listed in Table 1. Since no RGBs are obvious in any of the data sets, a straightforward conclusion is that there are no intrinsic populations of RGB stars in the (C)HVCs, and that the observed sources are mainly due to stars in the Milky Way and a few remaining unresolved background galaxies.

Since the Galactic foreground is comprised predominantly of red stars, the higher galactic latitudes of the new fields were not helpful in increasing our sensitivity to intrinsic blue stars. In contrast, the sensitivity of our new data for intrinsic, red stars improved by factors of 2 to 5. In Paper I, we carried out simulations to investigate how much of a stellar population we could add to the CMDs before we would notice the presences of blue or red plumes of stars indicative of young or old stellar populations intrinsic to the CHVCs. This served as an indication of the sensitivity limit of our survey. For the new data sets, we find that any putative young or old stellar

\[ \begin{align*}
\text{CHVC 224.0} & \text{–} 83.4 & \text{–} 197 \\
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\end{align*} \]

Figure 2. A plot of the positions of all sources detected in \( J \) and \( K_s \) toward CHVC 224.0–83.4–197. The position plots of the other targets are qualitatively similar.

\[ \begin{align*}
\text{CHVC 224.0} & \text{–} 83.4 & \text{–} 197 \\
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\end{align*} \]

Figure 3. The \( J, K_s \) CMD of CHVC 224.0–83.4–197. The CMDs of the other targets are qualitatively similar.
populations contribute between zero and a few per cent of stars detected on the optical CMDs. This indicates a sensitivity limit in V of 30 mag arcsec$^{-2}$ (cf. Paper I, Section 2.3).

The 2MASS position plots for the newly observed (C)HVCs show evenly distributed point sources across the fields without the kind of central source density increase which one would expect to see if there were stellar populations at the locations of the H$\alpha$ maxima of the (C)HVCs (see Fig. 2). This is despite the fact that the low Galactic foreground contributions favour the detection of smaller numbers of intrinsic stars.

Two of the fields exhibit one off-centre cluster of about a dozen sources each, with colours $J-K_s$ between 1 and 1.4 and at magnitudes where we might expect to detect the AGB of a stellar population intrinsic to the (C)HVCs. Upon further inspection, we find that both features can be explained with unresolved background galaxies belonging to known galaxy clusters. The CHVC 225.1$-$42.5$+$175 field exhibits these objects at RA = 67.49, Dec. = $-$26.38 and with $14 < K_s < 16$. The position coincides with the galaxy cluster Abell 0495. The field of CHVC 039.4$-$73.6$+$165 shows a clustering of sources at RA = 354.25, Dec. = $-$24.19 with $15 < K_s < 16$. The galaxy cluster Abell 2628 is located at this position; its member galaxies have redshifts of around 0.185. We checked that the near-infrared magnitudes and colours of the sources that we detect with 2MASS can be explained with those of galaxies using evolutionary models (e.g. Maraston 1998).

The 2MASS CMDs exhibit the same features as those shown in Paper I, displaying two pronounced plumes of stars at $J-K_s$ of about 0.3 and 0.8, and a less populated one at colours in between (Fig. 3). In contrast, dwarf galaxies of the Local Group show the blue plume of young stars near $J-K_s \approx 0$, as well as giant branches that are easily detected via horizontal fingers of AGB stars with colours $>1.4$. The near-infrared CMDs of the (C)HVCs do not resemble those of Local Group dwarfs, but rather that of Galactic stars.

As discussed in Paper I, 2MASS data are sensitive to young MS stars out to about 125 Kpc and to BSGs out to 500 Kpc. Only a few sources are seen in the CMDs of the newly observed (C)HVCs with colours and magnitudes that would correspond to such populations of stars. Therefore, we conclude that any luminous young stellar populations contribute less than a few per cent of the stars to the near-infrared CMDs. 2MASS data are uniquely sensitive to carbon-rich thermally pulsing AGB stars out to about 300 Kpc. Again, only a few qualifying sources are seen in the CMDs of the (C)HVCs. The dozen sources that could have been interpreted as AGB stars in two (C)HVCs were explained with background clusters of galaxies above. Therefore, any luminous AGB stellar population presumed to be intrinsic to the clouds contributes less than a few per cent of the stars on the CMDs of the fields.

While the data in principle allow for the presence of a few stars intrinsic to each of the five (C)HVCs we observed, the implied characteristics of the stellar content would be extremely different from that of all other dwarf galaxies of the Local Group. More likely, the (C)HVCs simply do not contain any stars. We interpret our observations as non-detections of stellar content associated with the (C)HVCs.

3.1 CHVC 224.0$-$83.4$+$197

CHVC 224.0$-$83.4$+$197 deserves a few additional comments. It is located on the sightline to the background quasar Ton S210, and has a sufficient H I column density to produce Lyman series absorption lines in the far-ultraviolet. Sembach et al. (2002) recorded the absorption spectrum of the CHVC, and used it to derive an upper limit to its metallicity. As the upper limit is below that of the O/H ratio of the local interstellar medium, they hypothesize that CHVC 224.0$-$83.4$+$197 could represent an extragalactic cloud of gas.

Our VLT observations do not include the sightline to the quasi-stellar object (QSO), as they were centred on the H I column density maximum of CHVC 224.0$-$83.4$+$197. The CMD of the FORS field is shown in Fig. 1. If the clumping of faint stars near $J$ of about 24.2 were interpreted as the TRGB of a metal-poor CHVC stellar population, then this would place the cloud at a distance of more than 4 Mpc. We consider this to be an unlikely explanation of the data, since the Galactic foreground naturally provides an increase of sources toward faint magnitudes in all of the CMDs observed.

The 2MASS source positions for the field surrounding the HI maximum of CHVC 224.0$-$83.4$+$197 are shown in Fig. 2 and the corresponding $J-K_s$ CMD in Fig. 3. The 2MASS field includes the sightline to Ton S210. There is nothing special associated in the positional distribution of the sources near the QSO sightline. The near-infrared CMD is not sensitive to a population of red giants at Mpc distances and cannot be used to confirm that the faint optical sources are due to stars at such a distance. However, just like the optical CMD, the near-infrared CMD of CHVC 224.0$-$83.4$+$197 is naturally explained with stars on a Galactic sightline at high latitudes, and does not require the assumption of an extragalactic stellar content associated with the cloud.

4 DISCUSSION

We begin by discussing in how much the hypothesis that HVCs form the repository of missing Local Group dwarf galaxies predicted by cosmological simulations is constrained by the data. We have observed 10 (C)HVCs to similar limiting magnitudes. All 10 cases are interpreted as non-detections of stellar content. We use binomial statistic to ask what is the probability to get zero success in 10 trials. Specifically, the zero detection of stellar content in our sample of 10 HVCs can be used to set limits on the true fraction of HVCs which may contain stars. There is a 50 per cent chance of getting a null result in 10 trials if fewer than 7 per cent of all HVCs contain stars. Assuming that the total sample of HVCs that can be interpreted as infalling building blocks following Blitz et al. (1999) amounts to 582 (Putman 2006), we therefore cannot exclude the possibility that 41 HVCs are undiscovered dwarf galaxies of the Local Group.

The CMD approach to search for stars in HVCs has also been used by other teams. Table 2 gives a list of (C)HVCs which have been observed with single-star photometry in two or more filters, including reference to the work, the limiting V or $K$ magnitudes achieved by the data and the names of the clouds studied. All searches yielded null results. The data are quite different in terms of limiting magnitudes and sky coverage. The data for HVC 267$+$26$+$216 are too shallow to be included in the statistical test. We also exclude the case of complex H, which was observed in the near-infrared, only. This leaves 16 (C)HVCs with which we can test the Blitz hypothesis out to a distance of about 600 Kpc. The non-detections of stellar content in 16 (C)HVCs is consistent with the hypothesis that less than 4 per cent of HVCs contain stars. Assuming that the 582 HVCs are uniformly distributed throughout a volume with a 1-Mpc radius, the data cannot exclude the possibility that 24 HVCs contain stars.

The observational biases for detecting dwarf galaxies around the Milky Way in the optical were recently discussed by Willman et al. (2004). The increased extinction and increase in Galactic foreground stars toward the disk, combined with the magnitude limits of surveys for overdensities of resolved stars, are predicted to account for a
that observational bias is not the easy way out of the substructure problem. If the predicted minihaloes do indeed exist, they do not contain stars.

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REFERENCES

Blitz L., Spergel D. N., Teuben P. J., Hartmann D., Burton W. B., 1999, ApJ, 514, 818
Braun R., in Hibbard J. E., Rupen M., van Gorkom J. H., eds, ASP Conf. Ser., Vol. 240, Gas and Galaxy Evolution. Astron. Soc. Pac., San Francisco, p. 479
Braun R., Burton W. R., 1999, A&A, 341, 437
Davies J., Sabatini S., Davies L., Linder S., Roberts S., Smith R., Evans Rh., 2002, MNRAS, 336, 155
Ganguly R., Sembach K. R., Tripp T. M., Savage B. D., 2005, ApJS, 157, 251
Hopp U., Schulte-Ladbeck R. E., Kerp J., 2003, MNRAS, 399, 33 (Paper I)
Klypin A., Kravtsov A. V., Valenzuela O., Prada F., 1999, ApJ, 522, 82
Kuijken K., Gilmore G., 1989, MNRAS, 239, 571
Lee M. G., Freedman W. L., Madore B. F., 1993, ApJ, 417, 553
Maraston C., 1998, MNRAS, 300, 872
Mateo M., 1998, ARA&A, 36, 435
Moore B., Ghigna S., Governato F., Lake G., Quinn T., Stadel J., Tozzi P., 1999, ApJ, 524, L19
Pisano D. J., Barnes D. G., Gibson B. K., Staveley-Smith L., Freeman K. C., Kilborn V. A., 2005, preprint (astro-ph/0509226)
Putman M. E., 2006, ApJ, 645, 1164
Putman M. E. et al., 2002, AJ, 123, 873
Robin A. C., Reyle C., Derriere S., Picard S., 2003, A&A, 409, 523
Schlegel D. J., Finkbeiner D. P., Davis M., 1998, ApJ, 500, 525
Sembach K. R., Gibson B. K., Fenner Y., Putman M. E., 2002, ApJ, 572, 178
Siegel M. H., Majewski S. R., Gallart C., Sohn S., Kunkel W. E., Braun R., 2005, ApJ, 623, 181
Simon J. D., Blitz L., 2002, ApJ, 574, 726
Simon J. D., Blitz L., Cole A. A., Weinberg M. D., Cohen M., 2006, ApJ, 640, 270
Wakker B. P., van Woerden H., 1997, ARA&A, 35, 217
Westmeier T., 2003, Diploma thesis, Rheinische Friedrich-Wilhelms-Universität Bonn
Westmeier T., Brüns C., Kerp J., 2005, in Braun R., ed., ASP Conf. Ser., Vol. 331. Astron. Soc. Pac., San Francisco, p. 105
Willman B., Dalcanton J., Ivezic Z., Schneider D. P., York D. G., 2002, AJ, 124, 2600
Willman B., Governato F., Dalcanton J. J., Reed D., Quinn T., 2004, MNRAS, 353, 639
Zwaan M. A., 2001, MNRAS, 325, 1142

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5 CONCLUSIONS

The zero detection of stellar content in our sample of 10 HVCs tightens constraints on the true fraction of HVCs which may contain stars. There is a 50 per cent chance of getting a null result in 10 trials if fewer than 7 per cent of all HVCs contain stars. We find that HVCs are a very unlikely source to provide the ‘missing’ dwarf galaxies of the Local Group which are predicted by cosmological simulations. It is becoming very apparent that the ‘missing’ satellites have not simply been overlooked observationally, indicating that observational bias is not the easy way out of the substructure

Table 2. (Compact) HVCs which have been searched for resolved stars.

| Team          | V limits | K limits | Identifier |
|---------------|----------|----------|------------|
| Davies et al. (2002) | 23.3     | N/A      | HVC 125+41–207 |
|               |          |          | HVC 070+51–146 |
|               |          |          | HVC 018+47–145 |
| Paper I       | 25–26    | 15.5     | HIPASS J1712–64 |
|               |          |          | HVC032–31–299 |
|               |          |          | HVC039–31–265 |
|               |          |          | HVC039–33–260 |
|               |          |          | HVC039–37–231 |
| Siegel et al. (2005) | 21.8     | N/A      | CHVC 017–25–218 |
|               |          |          | CHVC 030–51–119 |
|               |          |          | CHVC 271+29+181 |
|               |          |          | HVC 267+26+216 |
| Simon et al. (2006) | N/A      | 15       | Complex H |
| This work     | 26.25    | 15.5     | CHVC 039.4–73.6–165 |
|               |          |          | CHVC 224.0–83.4–197 |
|               |          |          | HVC 229–74–168 |
|               |          |          | CHVC 225.1–42.5+175 |
|               |          |          | HVC 225–42+190 |

total of 14–18 undetected dwarf satellites. Like our own work, this estimate assumes that the properties of the missed satellites are similar to those of the already known satellites.

In summary, the observational selection effects indicate that a few tens of dwarf galaxies may have been overlooked, but they cannot account for a few hundred ‘missing’ dwarfs.

We now turn to the issue of the nature of HVCs. Unless the associated stellar content is unlike that of any other known dwarf galaxy, we must conclude that HVCs simply do not contain stars and are best explained as pure gas clouds. Lacking the detection of stellar ‘standard candles’, the CMD work has not aided in determining the distances of HVCs. However, recent indirect distance constraints for HVCs have come from deep H I observations of M31 (Westmeier, Brün & Kerp 2005) and of other galaxy groups (Zwaan 2001; Pisano et al. 2005). These works place the HVCs within the extended Galactic halo, rather than throughout the Local Group. The ionization patterns observed in a few highly ionized HVCs also suggest a location of at least these clouds, in the Galactic halo or corona (e.g. Ganguly et al. 2005).