High Velocity Clouds: Dark Matter Dominated Failed Galaxies?

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1. HVCs and the Local Group Hypothesis
2. Four tests of the Hypothesis and why it has fallen from favor.
3. New observations + theory
4. Conclusions
High Velocity Clouds are clouds of atomic hydrogen with velocities incompatible with circular rotation about the Galactic center.
High Velocity Clouds are clouds of atomic hydrogen with velocities incompatible with circular rotation about the Galactic center.
Distribution on the Sky

Wakker (1999)
High Velocity HI Clouds

Cover >40% of the sky
No Galactic Plane, No Galactic Rotation
and yet... $|V_{\text{max}}| < 300$ km/s
Are the HVCs of Composite Origin?

- HVCs have a range of angular sizes from a few arcmin to 2000 square degrees:
  - Giant HVCs: 100 sq deg – 2000 sq deg
  - Compact HVCs: several sq deg
  - UCHVCs: 3 – 20 arc min

- Distances measured only to Giant HVCs:
  - 5 – 10 kpc Nearby

- Mass and binding depend on distance:
  - At 500 kpc typical mass is $\sim 10^7 M_\odot$ Need $\sim 10^8 M_\odot$ to be self-gravitating. All HVCs require additional mass to be self-gravitating.
What binds them together?

- **Stars?**
  
  As of 2012, no stars found in 250 HVCs despite careful searches – therefore no direct distances possible

- **Gas self-gravity?**
  
  Only if they are typically at distance of ~10 Mpc (then would be part of Hubble flow – velocities too small)

- **External Pressure?**

  Requires hot circumgalactic halo

- **Dark Matter?**

  Implies distance of ~500 kpc for 20% luminous matter content (amenable to various tests)
Distribution on the Sky
minus the largest complexes

Wakker (1999)
Global Kinematics

Wakker (1999)
Kinematics of the Ensemble of HVCs

Local Standard of Rest

Galactic Standard of Rest
A simple dynamical model for the HVCs

Milky Way and M31 have 95% of mass of the LG. Do CDM simulation to get present separation and velocity of MW & M31.

Associate the HVCs with mini-halos. Can be dynamically stable for a Hubble time. Ought to have low metallicity. Could be failed dwarf galaxies. Ought to have counterparts everywhere.

Time since Big Bang: 0.19 billion years
2.4 million light-years

Via Lactea 2 – courtesy of Michael Kuhlen
Local Group Hypothesis
Spatial Comparison

Blitz et al. 1999
Local Group Hypothesis
Kinematics Comparison
Local Group Hypothesis
Kinematics Comparison

Sherfesee, Thacker & Blitz
### Mean Properties of HVCs at 500 kpc

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI Mass</td>
<td>$4 \times 10^6 , M_\odot$</td>
</tr>
<tr>
<td>Total Mass</td>
<td>$2 \times 10^8 , M_\odot$</td>
</tr>
<tr>
<td>Diameter</td>
<td>14 kpc</td>
</tr>
<tr>
<td>$&lt;n(\text{HI})&gt;$</td>
<td>$5 \times 10^{-4} , \text{cm}^{-3}$</td>
</tr>
</tbody>
</table>

HI mass of all HVCs $\sim 10^9 \, M_\odot$

**NB:** No distances except to a few biggest (i.e. nearest?) HVCs
# Tests of the Local Group Hypothesis

1. **The Hα Test** (Bland-Hawthorne et al. 1998)

2. **The Metallicity Test** (Wakker et al. 1999; Gibson et al. 2001)

3. **The MgII Absorber Test** (Charlton et al. 2000)

4. **The Extragalactic Analogue Test** (Thilker et al. 2004)
55 of 58 lines of sight with MgII absorption have detected galaxies consistent with path through disk as shown above.

HVCs have about a factor of 2 more covering area than galaxies with parameters as above.

There seems to be little room left for HVCs in these systems.
Tests of the Local Group Hypothesis

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The Extragalactic Analogue Test

Are there ANY extragalactic HVCs?

~250 HVCs show no evidence for stars at 1 mag arcsec\(^{-2}\) fainter than faintest Local Group dSph as of 2001. Simon & Blitz (2001)

\[ D = 3.2 \text{ Mpc} \]
\[ d = 15 \text{ kpc} \]
\[ M = 1.7 \times 10^7 \text{ M}_\odot \]

Kilborn et al. (2000)
HVCs in M31

Seen to about 50 kpc from the center.
But are there enough of them?

<table>
<thead>
<tr>
<th>Targeted HI Arecibo Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Observed 6 Groups similar to LG</td>
</tr>
<tr>
<td>• Some with mass sensitivity of $7 \times 10^6 , M_\odot$</td>
</tr>
<tr>
<td>• Should have detected 6 – 23 clouds</td>
</tr>
</tbody>
</table>

Zwaan (2001)

Detected: 2(?)
Are minhalo-bound HVCs consistent with simulations and multiphase ISM?

Sternberg, McKee and Wolfire 2002

1. Interferometric observations exhibit 2 phase ISM. (de Heij et al. 2002)
   • Requires minimum external pressure of $P_{\text{EXT}}/k = 20 \text{ K cm}^{-3}$.

2. Compare to concentration-mass relationship of small halos from simulations.

$$\chi_{\text{vir}} = r_{\text{vir}}/r_s$$

$$\chi_{\text{vir}} = 27 \times 10^{0.14\sigma} (M_{\text{vir}}/10^9 \text{ M}_\odot)^{-0.08}$$

3. Looked at Burkert and NFW DM density profiles.
Are minhalo-bound HVCs consistent with simulations and multiphase ISM?

Sternberg, McKee and Wolfire 2002

1. Successfully modeled HI structure of two LG dwarf galaxies (Leo A and Sgr DIG). – distances are well determined.

2. Determine scale heights of HI gas assuming distance for HVCs of 750 kpc.

3. Models require 4 – 6 \( \sigma \) underconcentrated halos for HVCs bound by minihalos to have such large scale heights.

4. Local Group models require reduced bounding pressures making it difficult to form multiphase ISM.

5. Successfully model minihalos if distance is < 150 kpc.

BUT NO KINEMATIC MODELING
Perhaps the HVCs are not self-gravitating
Maller & Bullock (2004)

1. Assumed that the clouds are the result of a thermal instability in a hot (~10^6 K) circumgalactic halo.
2. Compared properties to CHVCs from Braun & Burton (2000).
   • Velocity dispersion of individual clouds close to observed value of 25 kms^{-1} FWHM.
   • Cloud-cloud velocity dispersion close to value observed for GSR distribution (115 km s^{-1}).
   • Get required masses close to “observed” value (3-5 x 10^6 M_☉).
   • Find about 4000 clouds (on the high side).

BUT NO KINEMATIC MODELING
**Thermal Instability Model for HVCs**

Maller & Bullock (2004)

- Can get the kinematics and distribution correct?

**hot, low density halo**

- Makes a higher metallicity plausible
- Brings many clouds in closer – possible solution for Hα, OVI, MgII observations

**Milky Way**
- \( T \sim 10^6 \text{ K} \)
- \( n \sim 2 \times 10^{-5} \text{ cm}^{-3} \)
- \( P/k \sim 20 \text{ K cm}^{-3} \)
- \( M \sim 10^{10} \text{ M}_\odot \)

**M31**
- barycenter
Thermal Instability Model for HVCs

Maller & Bullock (2004)

- Can get the kinematics and distribution correct?

1. Makes a higher metallicity plausible
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UCHVC HI Maps – 20 of 59 objects from ALFALFA survey

Mean properties for $d = 1$Mpc

$\theta = 10$ arcmin
$D = 2.9$ kpc
$M(\text{HI}) = 1.8 \times 10^5 \, M_\odot$
$M_{\text{DYN}} = 3.3 \times 10^7 \, M_\odot$
$\text{FWHM} = 23 \, \text{km s}^{-1}$

Adams et al. 2013
<table>
<thead>
<tr>
<th>CHVCs vs UCHVCs</th>
<th>Mean properties for UCHVCS ( d = 1 \text{Mpc} )</th>
<th>Mean properties for CHVCs ( d = 1 \text{Mpc} )</th>
</tr>
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<tbody>
<tr>
<td>( \Theta = 10 \text{ arcmin} )</td>
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<td>( \Theta = 60 \text{ arcmin} )</td>
</tr>
<tr>
<td>( D = 2.9 \text{ kpc} )</td>
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<td>( D = 15.6 \text{ kpc} )</td>
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<td>( M(\text{HI}) = 1.8 \times 10^5 \text{ M}_\odot )</td>
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<td>( \text{FWHM} = 23 \text{ km s}^{-1} )</td>
<td>( \text{FWHM} = 25 \text{ km s}^{-1} )</td>
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<tr>
<td>( N(\text{HI}) \sim 0.6 \times 10^{19} \text{ cm}^{-3} )</td>
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A UCHVC surrounding an Ultrafaint dwarf Leo P

Giovanelli et al. 2013
Leo P HI Rotation Curve

Giovanelli et al. 2013
Leo P

Distance $\sim 1.3 - 2$ Mpc

Currently forming stars

Very low oxygen abundance $12 + \log (O/H) = 7.17$

Normal $\alpha$ abundances

$V(\text{rot}) = 10 \, \text{km s}^{-1}$

Rhode et al. 2013; Skillman et al. 2013
Can models be made for UCHVCs incorporating dark matter?

Faerman, Sternberg & McKee (in preparation)

Minihalo Models for UCHVCs

HIM (pressure)
dark matter halo (gravity)

Sternberg McKee & Wolfire 2002
Faerman, Sternberg & McKee 2013

metagalactic radiation field

self-consistent radiative-transfer, heating & cooling, and hydrostatics (no rotation)
Can models be made for UCHVCs incorporating dark matter?

Faerman, Sternberg & McKee (in preparation)
Can models be made for UCHVCs incorporating dark matter?

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CHVCs require a low IGM pressure for multi-phase ISM. But if also have DM, it must be underconcentrated.

UCHVCs do not need such low pressures and can be bound with normally concentrated halos.
HVC Complex H -- a Dwarf Galaxy in a Retrograde Orbit?

- $R = 33 \pm 9\text{ kpc}$
- $d = 27 \pm 9\text{ kpc}$
- $M_{HI} = 6 \times 10^6 M_\odot$
- Size = $10 \times 5\text{ kpc}$
- $P/k = 100\text{ cm}^{-3}\text{ K}$
- $M_{dyn} \approx 10^8 M_\odot$

HVC colliding with the Milky Way?

Lockman et al. (2008)

- Apparent interaction with disk.
- 3 methods suggest $d = 12.4$ kpc
- $M(\text{HI}) = 10^6 \, M_\odot$
- $M(\text{dyn}) = 2.5 \times 10^7 \, M_\odot$

All dwarf galaxies in local group with distances > 250 kpc have HI clouds with masses > $10^6 \, M_\odot$. Do all clouds with this mass have embedded dwarf galaxies and DM?
HI in Local Group Dwarf Galaxies

Blitz & Robishaw (2000)

Suggests Ram Pressure Stripping

\[ n \sim 2.5 \times 10^{-5} \text{ cm}^{-3}; \ R = 250 \text{ kpc} \]
HI in Local Group Dwarf Galaxies

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Grcevich & Putman (2010)
M106 Group

Bauermeister et al. 2012
M106 Group

Bauermeister et al. 2012
Conclusions

1. There is scant evidence that the CHVCs, which make up the bulk of classical HVCs, harbor dark matter.

2. There is reasonable evidence that some of the Giant HVCs have embedded dark matter.

3. There is strong evidence that at least one UCHVC contains dark matter.

4. This is indirect evidence that other UCHVCs contain dark matter.

5. Are the UCHVCs the missing satellites?

6. Kinematic models of HVC hypotheses are sorely lacking.