LOW HI COLUMN HIGH-VELOCITY CLOUDS (HVC): GALACTIC OR EXTRAGALACTIC?

Nicolas Lehner
University of Notre Dame

Main collaborator: Chris Howk

Zech et al. 2008

Image Credit: Wakker & Richter SciAm 2004
HVC Probes of Outflow/Inflow, IGM,…

Images from Wakker & Richter, 2004, SciAm
See also, e.g.,
Sembach et al. 2003,
Nicastro et al. 2003,
Blitz et al. 1999
Putman et al. 2003
Fox et al. 2006,
Collins et al. 2005
HVCs exhibit H I 21cm emission that covers ~37% of the sky at $N_{\text{HI}} > 7 \times 10^{17}$ cm$^{-2}$ (Murphy et al. 1995). Observations motivated by the >50% Mg II detection rate from FOS Key project (Savage et al. 1993) compared to 18% HI covering factor at $N_{\text{HI}} > 2 \times 10^{18}$ cm$^{-2}$ (Wakker 1991).

Knowledge on distances, ionization, metallicities have only started to be estimated in the last ~15 years thanks in part to HST, FUSE, and ground based observations.
60% – 85% of sky covered at $N(\text{H}^+) \geq 10^{18} \text{ cm}^{-2}$ (for SMC metallicity)

Sembach, Wakker, Savage, et al. 2003
See also Fox et al. 2006, Collins et al. 2007
Si III HVC Galactic Sky

Si III HVC coverage about 80-90%.

\[ N_{\text{HII}} \approx (6 \times 10^{18} \text{ cm}^{-2})(Z_{\text{Si}}/0.2Z_{\text{sun}})^{-1}; \text{typical neutral fractions } N_{\text{HI}}/N_{\text{H}} \approx 0.01 \]

\[ M_{\text{HVC}} \sim 10^7 M_{\text{sun}} \left( d_{\text{HVC}}/10 \text{ kpc} \right)^2 \left( Z_{\text{HVC}}/0.2Z_{\text{sun}} \right)^{-1} \rightarrow <0.1 \text{ to } 1 \text{ solar mass per year} \]

(see also Richter et al. 2009 for Call observations)
HVCs with $N(\text{HI}) > 10^{19}$ cm$^{-2}$ are found toward distant and high z-height stars:
Complex C at 10 kpc
Complex M at <4 kpc
Complex A at 4-10 kpc
(e.g., Wakker 2001, Wakker et al. 2007, Thom et al. 2008).

**Cycle 17 Program:**
24 stars at $3<d<32$ kpc and $3<z<13$ kpc
Blind survey
COS G130M & G160M and STIS E140M
24 orbits

Illustration source: Wakker & Richter, SciAM, 2004
The Cycle 17 HST COS/STIS Program

4 < d < 32 kpc
3 < z < 13 kpc
First Example of Low HI Column HVCs Toward a Star

Two negative HVCs toward the center of the Galaxy at 7.5 kpc and z=+5.3 kpc

- OVI and HI absorption lines are also detected thanks to FUSE observations.

- Relative abundances:
  [Fe/Si] = -0.3, [Al/Si] = -0.3
  \[ \text{⇒ Evidence of dust} \]
  \[ \text{⇒ Likely a Galactic Origin} \]
  \[ \text{⇒ Galactic outflow, fountain} \]

- With OI and HI, we can directly deduce that: [O/H]=+0.2, supersolar abundance
  \[ \text{⇒ Galactic Origin!} \]
  \[ \text{⇒ Galactic fountain} \]

Very ionized, HII/H=0.97, HII/HI>>1
(N(HI)=10^{16.7} \text{ cm}^{-2})
Example of Negative-Velocity HVCs Toward a Star

Two negative HVCs at d<15 kpc and z<6 kpc

- At -118 km/s: Galactic Outer arm, first direct distance estimate of this Galactic arm (d≤15 kpc, Galactocentric radius 17.7 kpc).

- At -180 km/s: 
  - [Fe/Si]<+0.2, [Al/Si]~+0.1, [C/Si]~0
  ⇒ No evidence of dust
  ⇒ Likely an Extragalactic Origin
  ⇒ Accretion
  - [O I/Si II]~ -0.5, [O I/C II]~ -0.5
  -> Very ionized, HII/HI>>1

If 0.3 solar abundance,
N(H II) ≥ 10^{18.2} cm^{-2}
N(H I) ~ 10^{17.7} cm^{-2}

Example of a Positive-Velocity HVC Toward a Star

HVC at d<16 kpc and z<+8.4 kpc

[Fe/S] < -1.5, [Al/S] > -1.0
[Si/S] ~ -1.2, [Fe/Si]< -0.3
⇒ Evidence of dust
⇒ Likely a Galactic Origin
⇒ Galactic outflow, fountain

[O I/Si II]~ -0.7, [O I/S II]~ -2.1
-> Very ionized, HII/HI>>1

If solar abundance,
N(H II) ≥ 10^{19.5} cm^{-2}
N(H I) ~ 10^{17.3} cm^{-2}

Lehner & Howk 2011
HVCs toward Galactic stars (star symbols) with z-heights (kpc) and QSOs (circles, SiIII)

Lehner & Howk 2011 (star symbols); Collins et al. 2010 (circles)
## Detection Rate Comparison between Galactic and Extragalactic Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>HVC Detection Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QSO sightlines – Si III (a)</td>
<td>80-90</td>
</tr>
<tr>
<td>QSO sightlines – O VI (b)</td>
<td>60-90</td>
</tr>
<tr>
<td>H I emission (&gt;7×10^{17} cm^{−2}) (c)</td>
<td>37</td>
</tr>
<tr>
<td>Stellar sample (all)</td>
<td>50</td>
</tr>
<tr>
<td>Stellar sample (</td>
<td>z</td>
</tr>
</tbody>
</table>

(a) Collins et al. 2009, Shull et al. 2009; (b) Sembach et al. 2003, Fox et al. 2006; (c) Murphy et al. 1995; stellar sample: Lehner & Howk (2011)
Comparison of Properties between Galactic and Extragalactic Samples

<table>
<thead>
<tr>
<th>Extragalactic Sample</th>
<th>Stellar Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI, OVI, CIV, SiIV, SiIII, CII, SII, OI...</td>
<td>HI, OVI, CIV, SiIV, SiIII, CII, SII, OI...</td>
</tr>
<tr>
<td>H II/H I &gt;&gt; 1</td>
<td>H II/H I &gt;&gt; 1</td>
</tr>
<tr>
<td>[Z/H] ≤ 0 (3 HVCs with OI and HI)</td>
<td>[Z/H] = +0.2 for 1 HVC</td>
</tr>
</tbody>
</table>
| 100 < |v_{LSR}| < 400 km/s  
~100% of HVCs 100 < |v_{LSR}| < 200 km/s  
~25% of HVCs 200 < |v_{LSR}| < 400 km/s | 100 < |v_{LSR}| < 200 km/s |
| distance?  
Associated with Complex C ~ 10 kpc,  
Magellanic Stream ~ 50-100 kpc | 3<d< 30 kpc  
3<|z|<13 kpc |
| Origin(s)?  
Accretion, galactic interaction,  
outflow, WHIM(?)... | Origins:  
Galactic fountain/outflow  
Accretion (Galactic inflow) |
Other (low) N(HI) HVCs Near Galaxies

✓ HVCs between LMC and Milky Way (~50 kpc), probing the outflows from the LMC (Lehner et al. 2009, Staveley-Smith et al. 2003, Lehner & Howk 2007).

✓ HVCs detected toward other galaxies (M31, M33, e.g., Thilker et al. 2004, Westmeier et al. 2005, Putman et al. 2009).

✓ Lyman limit systems (HI $10^{16}$-$10^{19}$ cm$^{-2}$), likely higher redshift analogs of HVCs are found within <100 kpc from a galaxy (Stocke et al. 2010, Richter al. 2009, 2010, Lehner et al. 2009).

HVC: probes of galactic phenomena (accretion, outflow, galactic Interaction)
Summary

- Low HI column HVCs are unlikely to trace the warm-hot ionized medium.
- Instead many are located at $3 < |l| < 10$ kpc from the Milky Way plane, and probably within $<50-100$ kpc for most of them.
- They are therefore a key source of gas for future star formation and ingredient for studying the recycling of matter in the Universe.
- Our new understanding of the HVCs would not have been possible without HST and FUSE and the rich archive at MAST!
- Next few years look bright: COS observations of many QSOs will lead to better statistics/understanding of the covering factor, ionization, and metallicities.

Grazie mille - Thank you