Insights on the Galactic Center
Outflow from UV Absorption Lines

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The Fermi Bubbles: Theory and Observations
OUTLINE

- Introduction to UV studies of Galactic halo gas using high-velocity clouds (HVCs)

- Existing studies of HVC absorption in GC sightlines (|l| < 30°)

- Future studies of HVC absorption in GC sightlines
Gaseous Inflow and Outflow around Milky Way observed among the Galactic High-Velocity Clouds (HVCs) discovered in H I
• Sky covering fraction of HVC 21 cm emission ~37% (down to $N(\text{H I}) \sim 3 \times 10^{18} \text{ cm}^{-2}$; Murphy+ 1995)
• HVC metallicities ~0.1-1.0 solar; distances <~10 kpc (Lehner & Howk 2011, except MS & compact HVCs)
• Trace variety of processes (infall, Galactic fountain, tidal stripping, gas condensation)
HVCs in O \textsc{vi} 1031 absorption (*FUSE*, Far Ultraviolet)

- HVC O \textsc{vi}: 60-85\% sky coverage (Sembach+2003)
- Traces warm-hot plasma phase ($T \sim 300\ 000$ K)
HVCs in O \textsc{vi} 1031 absorption (\textit{FUSE}, Far Ultraviolet)

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HVCs in Si \textsc{iii} 1206 absorption (\textit{HST}, Near Ultraviolet)

- HVC Si \textsc{iii} : 91\pm 4\% sky coverage (Shull+ 2009)
- Traces cooler, photoionized gas at \sim 10^4 \text{ K}

Ionized gas ubiquitous in Galactic halo
Fox, Savage, & Wakker (2006) showed Highly Ionized HVCs seen in O\textsc{vi}/C\textsc{iv} but not at 21 cm (Sembach+1995, 1999; Collins+2004, 2005, 2006; Fox+2005, 2006; Zech+2008).

- **Red**: 200 to 400 km s\(^{-1}\)
- **Orange**: 100 to 200 km s\(^{-1}\)
- **Blue**: –400 to –150 km s\(^{-1}\)
- **Green**: –150 to –100 km s\(^{-1}\)
**HVC Distances**: new statistical method: Lehner & Howk 2011; Lehner+ 2012

Basic idea: compare HVC covering fractions toward stars & AGN

- **Stars** (known distance)
- **AGN** (effectively infinite distance)

- **Sun**
- **Disk**
- **Halo**
- **(GC)**
Scenario 1: HVCs distributed out to large distances (tens of kpc or more)
Scenario 2: HVCs located close to Galactic disk (<10 kpc)
HVC Covering Fractions measured from UV absorption lines

Lehner, Howk, Thom, Fox, et al 2012

- similar covering fraction toward stars (~50%) and AGN (~60%)
- measured from C II, Si II, Si III
- most HVCs lie in front of the halo stars, i.e. within ~10 kpc of the Sun
- based on 28 stars and 133 AGN
Part II: Existing UV absorption-line information on GC region
All-sky FUSE map of integrated O VI column toward extragalactic targets
Wakker, Savage, Fox, et al. 2012; GC-centered projection
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Keeney et al. (2006) studied GC outflow with HST/STIS & FUSE spectra of 2 AGN and 4 foreground stars:

AGN sightlines probe full GC region

Halo-star sightlines probe foregrounds (disk absorption, spiral-arm outflows)

Dotted and dashed lines show spectra of foreground stars, which do **not** show HVC components.

Keeney et al. 2006
Keeney et al. 2006

Mrk 1383

PKS 2005-489

Normalized Flux

C III λ977

O I

Si III λ1207

Si II λ1260

C II λ1036

C II* O VI

S II

Keeney et al. 2006

LSR Velocity [km s^{-1}]
Keeney et al. (2006) results

- detected 4 high-velocity ($|v_{\text{LSR}}| > 100$ km s$^{-1}$) components tracing the GC wind
- maximum $v_{\text{wind}} = 250 \pm 20$ km s$^{-1} <<$ calculated MW escape velocity ($\sim 550$ km s$^{-1}$)
- bound outflow reaching maximum $z$-height $12 \pm 1$ kpc (if motion is ballistic)
- launched $\sim 50$ Myr ago from GC region
- metallicity $\sim 0.1$-0.2 solar, surprisingly low for nuclear outflow (though depends on ionization corrections and values of H I column)
- HVCs appear similar to those observed in other (non-GC) directions
- No tracer of truly hot ($T > 10^6$ K) plasma present in UV (need X-ray)
Part III: What could be done with more UV observations
To test the vertical extent of the UV outflow, need targets at a range of latitudes.
Outflow signature: **positive-velocity wings** on the FUSE O VI absorption profiles in two anti-center directions (Fox+ 2006). The wings (excess absorption) reach $v_{\mathrm{LSR}}=+200$ km s$^{-1}$
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Need new data to search for wings in GC directions and constrain mass flow rate.
Distribution of O VI positive velocity wings, Sembach+ 2003
Still to be done in HVCs in GC directions:

Constrain ionization mechanism using high-ion column density ratios

Average values known in Galactic disk (green), halo (orange), and HVCs (red)
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Average values known in Galactic disk (green), halo (orange), and HVCs (red)
Enhanced C IV/O VI ratios would indicate turbulence in the wind
Summary

HVCs probe inflow/outflow/circulation around the MW.

Clear enhancement in O VI in Fermi Bubble region $|l| < 30^\circ$ (FUSE)

Multiple HVCs detected in 2 GC sightlines (1N+1S; Keeney+ 2006), interpreted as bound outflow reaching $z=12\pm1$ kpc ($\sim$size of FBs) launched $\sim50$ Myr ago

More HST data needed to constrain
- empirically how far UV outflow extends
- whether UV outflow is accelerating or decelerating
- whether absorption wings (outflow signatures) are seen in GC directions
- whether ionization mechanism shows trend with $z$-distance