Mapping Outflowing Gas in the Fermi Bubbles: A UV Absorption Survey of the Galactic Nuclear Wind

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Abstract

Using new ultraviolet (UV) spectra of five background quasars from the Cosmic Origins Spectrograph on the Hubble Space Telescope, we analyze the low-latitude (|b| = 20°–30°) regions of the Fermi Bubbles, the giant gamma-ray-emitting lobes at the Galactic Center. We combine these data with previous UV and atomic hydrogen (H I) data to build a comprehensive picture of the kinematics and metal column densities of the cool outflowing clouds entrained in the Fermi Bubbles. We find that the number of UV absorption components per sight line decreases as a function of increasing latitude, suggesting that the outflowing clouds become less common with increasing latitude. The Fermi Bubble H I clouds are accelerated up to \( v \approx 7\) km/s, whereas when we model the UV Fermi Bubbles clouds’ deprojected flow velocities, we find that they are flat or even accelerating with distance from the Galactic center. This trend, which holds in both the northern and southern hemispheres, indicates that the nuclear outflow accelerates clouds throughout the Fermi Bubbles or has an acceleration phase followed by a coasting phase. Finally, we note the existence of several blueshifted high-velocity clouds at latitudes exceeding \( \sim 30° \), whose velocities cannot be explained by gas clouds confined to the inside of the gamma-ray-defined Fermi Bubbles. These anomalous-velocity clouds are likely in front of the Fermi Bubbles and could be remnants from past nuclear outflows. Overall, these observations form a valuable set of empirical data on the properties of cool gas in nuclear winds from star-forming galaxies.

Unified Astronomy Thesaurus concepts: Milky Way Galaxy (1054); Milky Way evolution (1052); High-velocity clouds (735); Galactic center (565)

1. Introduction

The Fermi Bubbles are giant bipolar structures that originate from the center of the Milky Way. They each extend \( \sim 12 \) kpc or \( \sim 55° \) above and below the Milky Way’s disk in gamma-ray emission (Ackermann et al. 2014) and have counterparts in multiple wavelengths including X-ray emission, polarized radio emission, microwave emission, and UV absorption (Bland-Hawthorn & Cohen 2003; Dobler & Finkbeiner 2008; Dobler et al. 2010; Su et al. 2010; Carretti et al. 2013; Ackermann et al. 2014; Fox et al. 2015; Bordoloi et al. 2017b; Savage et al. 2017; Karim et al. 2018). The Fermi Bubbles are an example of a nuclear wind within our own galaxy; consequently, we can study them in detail and use them as analogs for feedback arising from similar mechanisms found in extragalactic sources (for a review of extragalactic and Galactic cool gas flows see Veilleux et al. 2020).

The origin of the Fermi Bubbles has been debated since their discovery, with two alternative energy sources invoked: the central supermassive black hole (Sgr A*) and star formation near the center of the Galaxy. Both mechanisms could supply the required energy to form the bubbles, but on very different timescales. In the Sgr A* origin scenario, the Bubbles formed in the last few megayears by either an accretion-disk wind or jet activity (Zubovas et al. 2011; Guo & Mathews 2012; Yang et al. 2012; Bland-Hawthorn et al. 2013, 2019; Mou et al. 2014). In the star formation-driven scenario, the Bubbles were formed by powerful star formation near the center of the Galaxy over the past \( \sim 30–100 \) Myr (Yusef-Zadeh et al. 2009; Lacki 2014; Crocker et al. 2015; Sarkar et al. 2015).

While it is possible that both Sgr A* and star formation contributed to the formation of the Bubbles, multiple lines of evidence now point toward Sgr A* as the primary origin because it explains the energetics on physically plausible timescales. Specifically, UV absorption-line and H I kinematic studies of clouds traveling within the Fermi Bubbles indicate an age of \( \sim 6–9 \) Myr (Fox et al. 2015; Bordoloi et al. 2017b; Di Teodoro et al. 2018), the same order of magnitude as Sgr A* formation model timescales, such as the Guo & Mathews (2012) jet formation models and Zubovas et al. (2011) accretion event models with timescales of \( 1–3 \) Myr and \( \sim 6 \) Myr, respectively. Furthermore, Bland-Hawthorn et al. (2013, 2019) find elevated levels of H α emission and UV ionization in the Magellanic Stream below the Galactic Center, consistent with the ionization cone that would be expected in a Seyfert flare event several megayears ago. Finally, a \( \sim 100 \) Myr extended period of star formation would have produced a large B-star population at the Galactic Center that is not observed unless an unusually top-heavy initial mass function is invoked.

Based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. These observations are associated with program 15339.
UV absorption-line data are essential for measuring the kinematics, metal content, and ionization levels of the cool gas ($T_{\text{gas}} \sim 10^4–10^5$ K) entrained in the Fermi Bubbles (Fox et al. 2015). Several studies have measured the UV absorption features of the Fermi Bubbles using sight lines to background quasars and, in two cases, a background star (Fox et al. 2015; Bordoloi et al. 2017b; Savage et al. 2017; Karim et al. 2018, hereafter, F15, B17, S17, and K18). The model-dependent results of these UV studies have revealed that the Fermi Bubbles have a cool gas mass of $\sim 2 \times 10^6$ $M_\odot$, a mass outflow rate of $\sim 0.2–0.3$ $M_\odot$ yr$^{-1}$, an outflow velocity of $\sim 800–1000$ km s$^{-1}$, and a wind age of $\sim 6–9$ Myr (F15; B17).

The Fermi Bubbles cover such a large angular extent on the sky ($\pm 55^\circ$ in latitude and $\pm 20^\circ$ in longitude) that there are multiple background sources with sufficient UV continuum for absorption studies using the Hubble Space Telescope (HST) Cosmic Origins Spectrograph (COS). However, past surveys have been limited to relatively high latitudes (|$b$| > 30$^\circ$) because foreground interstellar dust in the disk of the Milky Way extinguishes the light from background quasars (see Figure 1). Recently, Monroe et al. (2016) published a catalog of new UV-bright quasars which includes five new low-latitude sight lines that cover a large range of latitudes through the Fermi Bubbles ($-26^\circ \leq b \leq -16^\circ$). These new sight lines allow us to probe regions much closer to the launch point of the Bubbles than before in UV absorption and to search for variations in the Fermi Bubbles with Galactic longitude.

In this paper we present HST/COS data of these five new low-latitude quasar sight lines and combine them with previous UV samples (F15; B17; S17; K18) to give a comprehensive view of the UV absorption characteristics of the cool gas in the Fermi Bubbles. In Section 2 we discuss the observations and data reduction and the selection of high-velocity clouds (HVCs) associated with Galactic center activity. HVCs are defined as clouds moving at velocities in the local standard of rest (LSR) of $|v_{\text{LSR}}| \gtrsim 90$ km s$^{-1}$, which is too fast to be corotating with the Milky Way disk (Wakker & van Woerden 1997). Throughout the paper we will refer to the HVCs detected in the direction of the Fermi Bubbles as Fermi Bubble high-velocity clouds (FB HVCs) to distinguish them from other Galactic HVCs which are not associated with the Fermi Bubbles. We detail the results of the kinematics, ion column densities, and ion ratios of the FB HVCs in Section 3. Next, we discuss the results in Section 4. We conclude our paper in Section 5.

2. Observations and Methods

2.1. Far-ultraviolet Data

The new data analyzed in this paper were taken with HST/COS using the G130M and G160M far-ultraviolet (FUV) gratings. The absorption lines covered by this wavelength range include O I 1302, C II 1334, C IV 1548, 1550, Al II 1670, Ni II 1317, 1370, 1454 Si II 1190, 1193, 1260, 1304, 1526, Si III 1206, Si IV 1393, 1402, S II 1250, 1253, 1259, Fe II 1144, 1608, and N V 1238, 1242. The data were taken over a total of 22 HST orbits and have a signal-to-noise ratio (S/N) of 20 per resolution element. General information on the UV-bright background sources is given in Table 1.

The data were reduced with the calcos calibration pipeline twice, once using all photons collected and once using only the photons collected during orbital night; this “night-only” reduction reduces geocoronal airglow emission, which can strongly affect O I $\lambda$1302. After calcos was run, a further set of customized velocity alignment and coaddition steps was applied, following the procedures described in detail in the appendix of Wakker et al. (2015). This procedure aligns the detected Galactic absorption lines with the atomic hydrogen (H I) 21 cm emission-line data.

The data were binned by five pixels, and each absorption line was identified and measured using a Voigt profile fitting program, VPFIT (Carswell & Webb 2014). Initial guesses for
fit parameters (line centroid, column density, line width, and number of components) were first made using RDGEN, a collection of routines that is included with VPFIT. VPFIT then uses those initial guesses and finds the best-fit parameters for each component based on the chi-squared value of the fit, and will reject components that are not necessary to improve the goodness of fit. The wavelength-dependent COS line-spread functions were used in VPFIT to account for instrumental line broadening. Each fit was visually inspected.

While our fits to the data include absorption components at all velocities, our analysis is focused on the FB HVCs. In Fermi Bubble directions, the HVC kinematics (F15; S17) and the overabundance of HVCs (B17) compared to non-Fermi-Bubble directions supports the physical association of the HVCs with the Fermi Bubbles. We securely identified FB HVCs in the five new sight lines by only accepting HVCs that are detected in two or more metal lines. For this paper, we decided to use a novel approach to match velocity centroids in a statistically rigorous manner. In order for two absorption features to be labeled as part of the same FB HVC, we required their velocity centroids to match within three times their errors, where the errors are given by VPFIT. We discuss this error analysis in detail and its consequences in Section 2.3 and Appendix B.

An example of the calibrated data and resulting fits for UVQS J185302–415839 is shown in Figure 2; the fits to the four remaining new sight lines are presented in Appendix A as...
Figure A1. Intergalactic absorbers and absorption features inherent to the quasar are identified in each sight line and marked when visible in Figures 2 and A1.

2.2. Atomic Hydrogen 21 cm Data

For reference, atomic hydrogen (H I) 21 cm emission-line data from the Green Bank Observatory (GBT18A–221, PI: Fox) are included in the top-left panel for each sight line in Figure 2 when available. Spectra of the 21 cm H I line were obtained toward four of the five quasars using the 100 m diameter Robert C. Byrd Green Bank Telescope (GBT) of the Green Bank Observatory. The quasar UVQS J185649–544229 is below the horizon at Green Bank, so data from the Parkes Galactic All Sky Survey (GASS; McClure-Griffiths et al. 2009) were used instead. The GASS data have been rebinned by five channels.

The angular resolution of the GBT observations is 9′/1. Spectra were taken by frequency switching. The data were smoothed, calibrated, and corrected for stray radiation following the technique of Boothroyd et al. (2011), and a polynomial was fit to emission-free regions of the spectra to remove residual instrumental baseline. The polynomial order ranged from 3 to 7. The resulting spectra cover velocities −748 ≤ V_{LSR} ≤ +732 km s$^{-1}$ at a velocity resolution of 1 km s$^{-1}$. The rms brightness temperature noise in a 1 km s$^{-1}$ channel is 9.5 mK for all sources except for UVQS J193819–432626, where it is 11.5 mK. The resulting 5σ limit on the detectable H I column density, N_{H I}, for a 25 km s$^{-1}$ FWHM line is $4.3 \times 10^{17}$ cm$^{-2}$ except for J193819–432624, for which it is $5.2 \times 10^{17}$ cm$^{-2}$. The H I spectra displayed in Figure 2 have been smoothed to a velocity resolution of ∼5.3 km s$^{-1}$. Analysis of the H I spectra will be the topic of a separate paper.

2.3. Velocity Centroid Matching

Typically, absorption features are assumed to be real if they appear in two or more ions with matching velocity centroids and equivalent widths that are consistent with each line’s oscillator strength. How closely the velocity centroids of the absorption features have to match in order for them to be considered part of the same cloud is often open to interpretation. In this paper we quantified the proximity of velocity centroids and used these measurements to decide which features are likely living together in the same cloud.

VPFIT’s output includes a velocity centroid and velocity centroid error for each absorption feature fit. Additionally, there is an intrinsic zero-point error of ∼7.5 km s$^{-1}$ in each COS FUV grating (Plesha et al. 2019), which we add in quadrature to the velocity centroid error. We use these errors to match absorption features to each other within the same sight line.

First, we separate the absorption features into large groups based on their velocity centroids. Generally, the range of velocity centroids in a grouping attempts to capture absorption features that visually appeared to align in plots. However, we note that if a single FB HVC has two components separated by a large velocity, then they would be treated as separate clouds in these initial groupings. We assigned groups to the remaining absorption features based on their closest velocity centroid.

These initial groupings are shown in Table A1 as separated by horizontal lines.

The absorption features within each initial grouping are then matched based on their velocity errors. The velocity centroid offsets and errors between two ions are calculated using the following equations:

\[ \Delta v = v_2 - v_1, \tag{1} \]

\[ \sigma_v = \sqrt{(\epsilon_{v,2})^2 + (\epsilon_v,1)^2}, \tag{2} \]

where \( v_2 \) and \( v_1 \) are the velocity centroids of two different absorption features within the same initial group, and \( \epsilon_{v,2} \) and \( \epsilon_v,1 \) are their respective errors. The COS zero-point errors are only added to \( \epsilon_v \) (in quadrature) when the absorption features appeared on different gratings.

Next, the absorption features are matched to each other by comparing the results of Equations (1) and (2):

\[ \text{If } |\Delta v| > N \sigma_v, \text{ then no match} \]

\[ \frac{N \sigma_v}{\text{then match}}, \]

where we selected \( N = 3 \) to yield 3σ matches. We tested larger values of \( N \); however, we found that values greater than 3 resulted in separate absorption features from the same ion in the same pointing beginning to match. We therefore used \( N = 3 \) as a conservative value. Choosing a value of \( N = 3 \) also does not exclude a significant number of high–low ion pairs within an initial group that have velocity offsets, as discussed in detail in Appendix B. Equations (1) and (2) were used to find matches between every absorption feature in a group, resulting in a grid of matched and unmatched absorption features.

Finally, when all of the matches between individual ion pairs are made, all of the matched components within a visually aligned initial group are compared to decide which ones are part of the same cloud. This step is important for two cases: (1) absorption features with large velocity errors and (2) ions that have centroids matching some, but not all of the other ion centroids in a group. We do this by starting with the ion that has the lowest velocity centroid error and at least one matched ion. Then, we find all of the ions that are matched to it and also matched to each other (starting with the lowest velocity centroid errors and moving toward increasingly larger centroid errors). These ions are then grouped together as part of the same cloud. Ions that match some, but not all, of the ions in a cloud are marked as potentially being part of that cloud but we note that the result is inconclusive; these absorption features are not used in the calculations or graphs throughout the paper unless specifically stated otherwise. Column 10 of Table A1 indicates to which cloud each ion belongs. The matched absorption features are used to make all figures and calculations throughout this paper for all UV samples.

3. Results

Of the five new Fermi Bubble sight lines, three have FB HVCs detected in UV absorption. The directions without an FB HVC detection, UVQS J192636–182553 and UVQS J185649–544229, lie just outside and close to the edge of the gamma-ray-defined southern Fermi Bubble, respectively. In Table 2 we present basic information on the FB HVCs detected, including their velocity centroids and list of ions detected. In Appendix A, we provide a full table of fitted line parameters for Fermi Bubble high-velocity absorbers.
3.1. Incidence of Absorbers

In Figure 3 we plot the number of clouds per sight line detected in various ions against Galactic latitude and longitude to distinguish how the cool gas clouds are distributed in the bubbles. The bin sizes are 10° in latitude and 2° in longitude. We include our new observations and the samples of F15, B17, S17, and K18, forming what we refer to as the "full Fermi Bubble (FB) sample."

Each ion shows the same general trend with latitude in Figure 3(a): the number of clouds per sight line decreases rapidly beyond the $|b| = 0°–10°$ bin. Between $|b| = 10°$ and $40°$, there is a decrease in the number of absorbers per sight line. A linear fit to the data between $|b| = 10°$ and $40°$ results in a slope of $-0.08 \pm 0.02$. To test the quality of a monotonic fit to the data between latitudes of $10°$ and $40°$, we also performed a Spearman’s rank correlation test. The results of this test

| Sight Line       | $l$ (°) | $b$ (°) | Allowed Velocities$^a$ (km s$^{-1}$) | $v_{LSR}$ (km s$^{-1}$) | Error (km s$^{-1}$) | Ions Detected$^c$ |
|------------------|---------|---------|--------------------------------------|------------------------|-------------------|-----------------|
| UVQS J185302–415839 | 354.36  | -18.04  | -49 to 0                             | -121.9                 | 9.2               | O I, C II, Al II, Si II, Si III, C IV, Si IV |
|                  |         |         | -202.4                               | 9.9                    |                   | C II, Si III    |
|                  |         |         | 133.4                                | 10.9                   |                   | C II, Al II, Si II, C IV, Si IV |
|                  |         |         | 248.0                                | 9.4                    |                   | Si II, Si III  |
| UVQS J191928–295808 | 8.18    | -18.77  | 0–63                                 | 234.4                  | 8.9               | Si III, C IV   |
| UVQS J193819–432646 | 355.47  | -26.41  | -13 to 0                             | -104.4                 | 8.5               | C II, Si III, Si IV |

Notes.

$^a$ Range of velocities allowed for gas corotating with the disk, calculated following the methods outlined in Wakker (1991).

$^b$ The average velocity centroid of the matched ions in the last column.

$^c$ A list of matched ions that were found to be part of the same cloud via the process described in Section 2.3.
include the Spearman’s correlation coefficient ($\rho_S$) and a two-sided significance of the coefficient’s deviation from zero ($P$ value). The correlation coefficient has values from 0 to 1, and a high value indicates that the data have a strong monotonic relationship. The associated $P$ value indicates how likely it is that any monotonic relationship is due to chance. The data between $|b| = 10^\circ$ and $40^\circ$ have a $\rho_S$ of $-0.727$ and $P$ value of 0.002, indicating that the relationship is strongly monotonic.

From the $|b| = 30^\circ - 40^\circ$ bin to the $40^\circ - 50^\circ$ bin, there appears to be a small jump in the number of absorbers per sight line. This latitude corresponds to the upper boundary of the Fermi Bubbles, so the increasing incidence at that latitude may be due to the sight lines intersecting interface layers at the Bubble boundaries.

The absorbers in the $|b| = 0^\circ - 10^\circ$ bin are all detections from a single STIS/HST sight line, LS 4825, and the $|b| = 40^\circ - 50^\circ$ bin contains the STIS/HST sight line M5-ZNG19 (Zech et al. 2008; Savage et al. 2017). These STIS data have a resolution of 6.6–10 km s$^{-1}$ while COS data from the rest of the full Fermi Bubble sample have a resolution of 18–20 km s$^{-1}$. To determine if the high-resolution data from STIS are resulting in a larger number of absorbers per sight line, we have identified narrow STIS components from LS 4825 and M5-ZNG1 that would not have been resolved as separate features by COS. These components typically have small $b$ values ($\leq 10$ km s$^{-1}$) and overlap with adjacent absorbers (absorbers within $\leq 15$ km s$^{-1}$). Because these components would be unresolved as separate components in COS, we have counted them as a single absorber. We then removed any components that would be considered unmatched with the previously removed components. The results are shown in Figure 3(b). While the number of detections per sight line slightly decreases in the $|b| = 0^\circ - 10^\circ$ bin (and $|b| = 40^\circ - 50^\circ$ bin), the $|b| = 0^\circ - 10^\circ$ bin still contains a larger number of C IV, Si II, and Si IV absorbers than any of the other bins. This indicates that the large number of absorbers in the $|b| = 0^\circ - 10^\circ$ bin is not due entirely to the resolution differences in the STIS and COS data.

In Figure 3(c), the number of FB HVCs remains steady with longitude, except at the highest absolute longitudes. A linear fit to the data reveals a slope of $-0.33 \pm 0.09$. The data have a moderate monotonic relationship with a Spearman’s rank correlation coefficient of $-0.543$ and a $P$ value of 0.002. That monotonic relationship does not appear to be linear as indicated by the low significance of the linear fit’s slope.

### 3.2. Velocity Centroids

The dependence of FB HVC velocity on latitude and longitude is of great interest because it probes the velocity profile of the wind. This profile has been studied in earlier work: B17 and K18 found an anticorrelation between the maximum absolute LSR velocity of the detected gas, max $|v_{\text{LSR}}|$, and the absolute latitude, $|b|$. To determine whether the five new sight lines follow this trend and also to look for any trends in the previously unexplored axis of Galactic longitude, we plot the maximum cloud galactic standard of rest (GSR) absolute velocity (max $|v_{\text{GSR}}|$) against $|l|$ and $|b|$ in Figures 4(a) and (b), where

$$v_{\text{GSR}} = v_{\text{LSR}} + (\cos b \sin l)(254 \text{ km s}^{-1}).$$

We use a circular rotation velocity of 254 km s$^{-1}$ at the solar distance from the Galactic center (Reid et al. 2009). The translation to the GSR reference frame is important, since it removes the effect of Galactic rotation; the latitudinal profile of the wind is largely unaffected by this translation. To calculate an FB HVC velocity we have averaged the velocity centroids of the detected ions determined to be part of the same cloud. The error bars in Figure 4 are calculated by propagating the error of the average velocity centroids; these errors include the instrumental zero-point error. Three sight lines in the full Fermi Bubble sample, LS 4825, PKS 2005–489, and M5-ZNG1, have STIS UV data for which a zero-point offset of 1.7 km s$^{-1}$ was used (Sonnenrucker 2015). PKS 2005–489 has one FB HVC with FUSE data for which a zero-point offset of 10 km s$^{-1}$ was used (Sembroski et al. 2003). In Figure 4 the blue and red symbols indicate blueshifted and redshifted clouds, respectively, while the squares and circles indicate the northern and southern Fermi Bubbles, respectively.

We find that $|v_{\text{GSR}}|$ decreases with increasing latitude as shown in Figure 4(a). Linear fits to this trend yield

$$\max(|v_{\text{GSR}}|) = (-3.3 \pm 0.1)b + (305.3 \pm 3.1) \text{ km s}^{-1},$$

where $b$ is in degrees.

The dependence of maximum GSR velocity on Galactic longitude is shown in Figure 4(b). No clear monotonic trends are found in the current data set ($\rho_S = 0.225$ and $P$ value = 0.459).

To study the trends of velocity in both Fermi Bubbles separately and to better visualize any trends and symmetries, we have displayed a map of the maximum absolute GSR velocities in Figure 4(c). In this map, the size of the circle is scaled with velocity and the color of the circle represents redshifted/blueshifted components. In Figure 4(c) the velocities decrease with increasing latitude, which confirms the general trend seen in Figure 4(a). We do not see any obvious asymmetries in the maximum velocity of clouds in the northern and southern Fermi Bubbles.

### 3.3. Component Kinematics

As part of this study, we analyzed the kinematics of the FB HVC population. We focus on two separate kinematic measurements: the velocity centroid alignment between different ions and the distribution of component line widths ($b$ values) for different ions. Both of these measurements help us to determine which absorption components are part of the same FB HVC and to reveal the phase structure of the clouds, i.e., whether they are single phase or multiphase. The velocity offsets may also reveal the presence of any evaporative or condensing flows (Borkowska et al. 1990). For example, gas in collisional ionization equilibrium would result in lines that all have the same centroid velocity and line width, independent of whether they are high ions (C IV and Si IV) or low ions (C II and Si II). In contrast, a cool gas with an evaporative transition layer may give rise to velocity centroid offsets between the low and high ions. For a review of ionization mechanisms in HVCs, see Fox et al. (2004). Below we present the quantitative results of the velocity centroid matching and $b$-value analysis.
3.3.1. Velocity Centroid Offsets

We measured the difference between the velocity centroids ($\Delta v$) of different ions in each FB HVC. Using only the matched FB HVC components (velocity centroid offset $\leq 3\sigma$), we measured the mean $\Delta v$, the standard error of the mean, and the standard deviation of the mean for high–low, high–mid, mid–low, high–high, and low–low ion pairs (e.g., C IV–C II, Si IV–Si III, Si III–Si II, Si IV–C IV, and Si II–C II pairs, respectively). The standard error of the mean is a measure of the accuracy of the mean calculation when compared to the parametric mean and is equal to the standard deviation divided by the square root of the number of pairs. The $3\sigma$ cutoff imposed in our matching process does not bias these calculations toward low $\Delta v$ values compared to visual matching techniques, as discussed in Appendix B. We list the results in Table 3.

**Table 3**

| Ion Pair      | $\langle \Delta v \rangle$ (km s$^{-1}$) | Standard Error of the Mean (km s$^{-1}$) | Standard Deviation (km s$^{-1}$) | Number of Pairs |
|---------------|----------------------------------------|-----------------------------------------|---------------------------------|----------------|
| High–Low      | 9.3                                    | 1.2                                     | 9.4                             | 64             |
| High–Mid      | 7.8                                    | 1.7                                     | 7.8                             | 22             |
| Mid–Low       | 8.0                                    | 1.1                                     | 7.0                             | 43             |
| Low–Low       | 4.0                                    | 0.5                                     | 5.5                             | 146            |
| High–High     | 11.0                                   | 3.2                                     | 12.6                            | 16             |

Note. This table shows the mean velocity centroid offset, its standard error, and the standard deviation of $\Delta v$ for various ion pairs for all matched components in the full FB sample (including absorption features matched to some, but not all the lines in a given cloud).
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Figure 5. Distribution of $b$ values for FB HVCs in the full FB sample. The top panel compares C II and C IV and the bottom panel compares Si II, Si III, and Si IV. There is no statistical evidence for any differences between these distributions, as shown in Table 4.

3.3.2. Component Line Widths

The velocity width ($b$ value) of the individual ion absorption components encodes information on the thermal state of the gas. It contains thermal ($b_{\text{therm}}$) and nonthermal contributions ($b_{\text{non}}$), and can be generally written as $b^2 = b_{\text{therm}}^2 + b_{\text{non}}^2 = 2kT/Am + b_{\text{non}}^2$, where $A$ is the atomic weight of the ion.

In Figure 5 we compare the $b$-value distributions of the FB HVCs for C II and C IV (top panel) and for Si II, Si III, and Si IV (lower panel). We only compare ions of the same species, since thermal broadening is dependent on atomic weight. We combine all of our FB HVC data in this plot in order to analyze the general trends seen in the FB HVCs in a statistically significant manner. The mean $b$ values for silicon and carbon are 22.4 and 21.1, respectively.

Two-sided K-S tests were run to check for the statistical similarity of the $b$-value distributions of different ions. The resulting $P$ values and $D$ statistics are shown in Table 4. None of the K-S tests provide any evidence that the $b$ values are drawn from separate populations. Because we have not analyzed each FB HVC component separately, we cannot conclude with certainty that the high and low $b$ values for every FB HVC trace each other well. For example, PDS 456 and M5-ZNG1 each have two FB HVCs with high ion absorbers that are much broader than the low ion absorbers. Yet, in general, the trends in the $b$ values indicate that the high and low $b$ values are similar over the entire sample of FB HVCs. This indicates that interpreting the $b$-value distribution is not simple.

3.4. Ion Column Densities

Another key property of the FB HVC population is the dependence of column density on position, which may indicate changes in physical conditions of the clouds as they rise into the halo.

We have plotted the carbon and silicon ion column densities from all FB HVCs detected in the full FB sample and plotted them against Galactic latitude and longitude in Figure 6. C and Si are useful elements to trace because we can measure columns for each element in both high and low ions. We modeled a linear fit to each ion separately using the `survreg` function in the `survival` package from R\(^{10}\) (Therneau & Grambsch 2000). The `survival` package fits a parametric survival regression model, allowing the lower limits to be included in the linear fit model (errors for other measurements are not included in the model). For the calculations, we set the maximum number of iterations to be 100 and the assumed distribution of log $N$ to be Gaussian. The results are listed in Table 5. The standard error listed for each coefficient is a measure of the coefficient standard deviation, calculated by taking the square root of the variance-covariance matrix diagonal elements. The $P$ value is also listed for the $A$ coefficient (all $P$ values for intercepts were reported as $<2 \times 10^{-16}$). The results of the linear modeling indicate that none of the graphs in Figure 6 have a slope significantly greater than zero. We therefore conclude that there is no evidence in the current data for a change in the ion columns with latitude or longitude.

To study the column densities in both Fermi Bubbles separately and to better visualize any potential trends and symmetries, we have plotted maps of C II, C IV, Si II, and Si IV column densities for each FB HVC in Figure 7. In these maps, the size of the circle is scaled with log $N$ with the lowest column for each pointing indicated by a filled circle. No new trends or asymmetries are obvious in these plots.

3.5. Ion Ratios

The ionization level is another property of interest in the Fermi Bubble cloud population. This property can be diagnosed using the following UV line ratios: C IV/C II, Si IV/Si II, Si IV/Si III, and Si III/Si II. Each of these ratios compares two ions from the same element, thus ensuring that they are insensitive to dust depletion and absolute abundance variations. In a previous work, K18 did not find a trend in silicon ionization levels with latitude in their data when combined with the data of F15, B17, and S17.

Figure 8 displays the ion ratios for each FB HVC from the full FB sample and compares them with Galactic latitude and Galactic longitude. We modeled a linear fit to each ratio separately using the `survival` package in R for graphs

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Table 4: K-S Tests for $b$ Values

| Ions         | $D$  | $P$ Value |
|--------------|------|-----------|
| Si II and Si IV | 0.238 | 0.619     |
| Si II and Si III | 0.208 | 0.689     |
| Si III and Si IV | 0.318 | 0.251     |
| C II and C IV  | 0.286 | 0.604     |

Note. Two-sided KS tests were computed for each pair of ions shown for the data in Figure 5.

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\(^{10}\) https://CRAN.R-project.org/package=survival

\(^{11}\) https://www.R-project.org/
containing lower limits and using a combination of the survival and NADA\textsuperscript{12} packages in R for graphs containing upper limits. The NADA package handles upper limits to be included in the linear fit model from the survival package. For the calculations, we set the maximum number of iterations to be 100 and the assumed distribution of log $N$ to be Gaussian. The results are listed in Table 6. None of the slopes significantly deviate from zero; the current data do not indicate that the ion ratios are changing with latitude or longitude.

4. Discussion

With the full FB sample, we can now map the kinematics and ion properties of the outflowing cool gas in the bubbles. The five new sight lines in particular provide data in the low-latitude region ($b \approx 15^\circ$–$26^\circ$) close to the base of the Bubbles

\begin{table}[h]
\centering
\begin{tabular}{lllllll}
\hline

Equation & Element & $A$ & Standard Error & $P$ Value & $B$ & Standard Error \\
\hline

Galactic Latitude & log $N = Ab + B$ & C II & 0.0093 & 0.0083 & 0.262 & 13.60 & 0.27 \\
 & & C IV & $-0.0159$ & 0.0081 & 0.050 & 13.94 & 0.24 \\
 & & Si II & $-0.0199$ & 0.0064 & 0.002 & 13.78 & 0.19 \\
 & & Si IV & $-0.0018$ & 0.00572 & 0.160 & 13.05 & 0.17 \\

Galactic Longitude & log $N = Al + B$ & C II & 0.0495 & 0.0491 & 0.313 & 13.63 & 0.27 \\
 & & C IV & $-0.0672$ & 0.0565 & 0.234 & 13.84 & 0.28 \\
 & & Si II & $-0.0740$ & 0.036 & 0.038 & 13.64 & 0.21 \\
 & & Si IV & 0.0004 & 0.0329 & 0.990 & 12.86 & 0.18 \\

\hline
\end{tabular}
\caption{Dependence of Column Density on Latitude and Longitude}
\end{table}

Note. This table contains parameters from linear fit models to the ionic column densities versus latitude and longitude using parametric survival regression. The coefficients each have a standard error listed, and the $P$ values of the slope are also given (all $P$ values for $B$ were reported as $<2 \times 10^{-16}$).

\textsuperscript{12} https://CRAN.R-project.org/package=NADA
Figure 7. Plots of the ionic column density as a function of position for each FB HVC. Filled circles are the lowest column measurement for each pointing. The half circles represent lower limits. The size of each circle is scaled to column density, as shown in the key between plots denoted by black circles. The gray ovals denote the Miller & Bregman (2016) FB models.
where the nuclear outflow is launched. Of the five new sight lines through the Fermi Bubbles, three have at least one FB HVC detection. Of the total of 15 sight lines that pass clearly through the Fermi Bubbles from the full UV FB sample 12 or 80% have at least one FB HVC associated with them. In contrast, of the 54 sight lines lying outside of the Fermi Bubbles but still in the general vicinity of the Galactic Center, only 15 or 28% have HVC detections. These enhanced

Figure 8. Log of the column density ratios of FB HVCs as a function of latitude and longitude.
covering fractions support the physical association of HVCs with the Fermi Bubbles, confirming the result of B17.

4.1. Velocity Profile of the Fermi Bubbles
4.1.1. Velocity Profile Observations

Our analysis of the full FB UV sample reveals that the GSR velocity of the FB HVCs generally decreases with increasing latitude (Figure 4(a)), with the exception of one point at $b \sim 26^\circ$ and $v_{\text{LSR}} \sim 100 \text{ km s}^{-1}$. This cloud is from the UVQS J193819–432646 sight line and may represent foreground material or clouds with significant motion in the plane of the sky.

Recently published H I data from McClure-Griffiths et al. (2013), Di Teodoro et al. (2018), and Lockman et al. (2020) show clouds at low latitudes ($|b| < 7^\circ$) associated with nuclear outflow that are likely linked to the Fermi Bubbles. In Figure 9 we have combined these H I data with the full UV sample to show the full velocity profile of the Milky Way’s nuclear wind for the first time. The figure shows GSR velocity against absolute latitude. It is worth noting that at $b \approx 7^\circ$, where we have overlapping coverage between the radio and UV samples, there is a remarkable agreement in the range of velocities observed, with both radio and UV samples seeing gas at up to $\pm 300 \text{ km s}^{-1}$. This adds confidence to the idea that the radio and UV samples are tracing a similar population of clouds.

Clouds near the base of the Fermi Bubbles, seen in H I, are accelerated up to $|b| \sim 7^\circ$ (Lockman et al. 2020). After that point, the clouds (seen in the UV because the H I coverage does not currently extend that high into the halo) show a change in $v_{\text{GSR}}$ of $-0.3 \pm 0.1 \text{ km s}^{-1}$ per degree. As the clouds move upwards, their volume density decreases: the path length of the line of sight through the bubbles increases with increasing latitude (the bubbles are slimmer at lower latitudes) and, as seen in Figure 3, the number of UV-detected FB HVCs per unit path length decreases with increasing latitude.

We note that in Figure 9, the blueshifted UV data points beyond $\sim 30^\circ$ latitude are not likely located inside of the Fermi Bubbles due to the tangential velocity constraints imposed by the geometry of the Fermi Bubbles. At a Galactic latitude of $45^\circ$, the near side of the Fermi Bubbles is approximately perpendicular to the line of sight, resulting in a projected

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Table 6

| Equation | $A$ | Standard Error | $P$ Value | $B$ | Standard Error | $P$ Value |
|----------|-----|----------------|-----------|-----|----------------|-----------|
| Galactic Latitude | $\frac{C\ iv/C\ ii}{Si\ iv/Si\ ii}$ | $-0.0200$ | $0.0082$ | $0.015$ | $0.0723$ | $0.2632$ | $0.783$ |
| $\frac{Si\ iv/Si\ iii}{Si\ iii/Si\ ii}$ | | | | | | | |
| $= Ab + B$ | | | | | | | |
| $0.0057$ | $0.0056$ | $0.309$ | $-0.4308$ | $0.1657$ | $0.009$ |
| $-0.0016$ | $0.0071$ | $0.820$ | $-0.1708$ | $0.2590$ | $0.510$ |
| $0.0062$ | $0.0057$ | $0.208$ | $-0.2200$ | $0.1916$ | $0.250$ |
| Galactic Longitude | $\frac{C\ iv/C\ ii}{Si\ iv/Si\ ii}$ | $-0.0008$ | $0.0012$ | $0.478$ | $-0.3949$ | $0.2226$ | $0.076$ |
| $\frac{Si\ iv/Si\ iii}{Si\ iii/Si\ ii}$ | | | | | | | |
| $= Al + B$ | | | | | | | |
| $-0.0012$ | $0.0005$ | $0.019$ | $-0.1754$ | $0.1045$ | $0.093$ |
| $0.0007$ | $0.0007$ | $0.313$ | $-0.2916$ | $0.1215$ | $0.016$ |
| $-0.0008$ | $0.0008$ | $0.300$ | $0.0923$ | $0.1174$ | $0.430$ |

Note. This table contains parameters from results of linear fit models to the ionic ratios versus latitude and longitude using parametric survival regression. The coefficients each have a standard error and $P$ values listed.

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Figure 9. GSR velocity vs. absolute latitude (plotted on a log scale) of the combined H I and UV data from the Galactic center outflow. Red and blue symbols represent FB HVCs that are redshifted and blueshifted, respectively. Open squares and circles represent the H I data from McClure-Griffiths et al. (2013), Di Teodoro et al. (2018), and Lockman et al. (2020) from the northern and southern Fermi Bubbles, respectively. Filled squares and circles represent the UV data from the full FB sample from the northern and southern Fermi Bubbles, respectively.
velocity of zero km s$^{-1}$ (using the geometry outlined in Miller & Bregman 2016). Nonetheless, the blueshifted FB HVCs beyond $\sim 30^\circ$ latitude may still be related to the Fermi Bubbles since they follow the trend of Fermi Bubble clouds in $v_{\text{GSR}}$ versus Galactic latitude. One possibility is that these FB HVCs lie just outside of the current Fermi Bubbles and are remnants of past Galactic Center outbursts (assuming that the Fermi Bubbles are a cyclic/episodic process as suggested in Su & Finkbeiner 2012; Bland-Hawthorn et al. 2019); exploring their origin is beyond the scope of this paper.

### 4.1.2. Velocity Profile Model

The ambiguity in distances to the FB HVCs and the projection effects of their movement with respect to the plane of the sky makes it difficult to interpret the observed radial velocities. However, within the framework of some simplifying assumptions, we model the distribution of relative probabilities of FB HVC flow velocities in this section.

We use the Fermi Bubble geometry modeled by the equations in Section 5 of Bordoloi et al. (2017b). For details about the formulaic derivation of the geometry used in this paper, see Appendix C. This geometry assumes that the Fermi Bubbles can be modeled as two cones on opposite sides of the Galactic plane with identical opening half-angles of $\alpha_{\text{max}}$. Using the results of Di Teodoro et al. (2018), we assume an $\alpha_{\text{max}}$ of 70$^\circ$. This choice for $\alpha_{\text{max}}$ is consistent with the boundaries of the evacuated HI near the Galactic center shown on the left side of Figure 1 (Lockman & McClure-Griffiths 2016), assuming that the lack of H1 is the result of the same outflow discussed in Di Teodoro et al. (2018). This conic geometry with an $\alpha_{\text{max}}$ of 70$^\circ$ would not exclude the anomalous-velocity clouds beyond $\sim 30^\circ$ in latitude discussed in Section 4.1.1 from the interior of the Fermi Bubbles. The exclusion of the anomalous-velocity clouds is based on the Miller & Bregman (2016) bubble geometry. Given that the conic geometry does not restrict the velocities of these anomalous FB HVCs and that there is limited UV data available, the anomalous-velocity clouds have been included in the analysis of these models.

The FB HVCs are assumed to be launched from the vertex of the cone uniformly over all angles to a distance, $r$, defined as the distance from the vertex to some spot on the surface of a cone:

$$r = \frac{\rho \sin b + z}{\cos \alpha},$$

(5)

where $\rho$ is the distance from the cloud to the observer, $b$ is the Galactic latitude of the cloud, $z$ is the offset of the cone’s vertex from the center of the Galaxy, and $\alpha$ is the angle of a cone on which the cloud resides (nested within the boundary of the larger cone containing the whole flow). We include the parameter, $z$, in our equations to include the possibility that the flow arises a distance away from the Galactic plane from a ring surrounding the Galactic center. However, we set $z = 0$ in our analysis on the premise that if there was a $z$ component greater than 0, then an imprint of Galactic rotation would be expected in the flows, yet no such imprints are detected by Di Teodoro et al. (2018).

Using this geometry, we compute a differential probability $\Delta P$ per unit change in $v_{\text{flow}}$, where $v_{\text{flow}}$ is the deprojected velocity of the FB HVCs. The differential probability, $\Delta P$, is the probability of finding an individual cloud at some location within the Fermi Bubbles, which we have defined as equivalent to the density of the clouds. To define this density, we consider the volume between two nested cones, one with an opening half-angle $\alpha$ and another with this angle equal to $\alpha + \Delta \alpha$. The path length of the sight line that penetrates the space between these cones is given by the term $(dp/d\alpha)\Delta \alpha$. The volume density of the clouds in this volume would be proportional to the inverse square of the distance, $r$, if the clouds maintain their integrity and move at constant velocity. If the clouds are not moving at constant velocity, the density would be changed in proportion to the inverse of this velocity. Hence, the density of clouds with conserved mass should be proportional to $r^{-2}/v_{\text{flow}}$, where $v_{\text{flow}}$ is defined as

$$v_{\text{flow}} = \frac{v_{\text{GSR}}}{\cos \beta},$$

(6)

where $\beta$ is the angle between the flow direction and the line of sight.

The differential probability is therefore defined as

$$\Delta P = \frac{(dp/d\alpha)(dv_{\text{flow}}/d\alpha))r^q}{v_{\text{flow}}^{q+1}}\Delta \alpha,$$

(7)

where $q$ is a radial index that quantifies how much of the clouds’ mass is conserved as they travel to larger $r$. A value of $q = -2$ describes clouds that have their mass conserved as they flow to higher $r$, and a value of $q < -2$ describes clouds that are being eroded by the flow. For each value of $\alpha$, one can evaluate the transformation from $v_{\text{flow}}$ to $v_{\text{obs}}$ from the dot product of the unit vectors that represent the flow direction and the line of sight direction.

Figure 10 shows the sums of the probabilities, $\Delta P$, as a function of distance from the Galactic center and flow velocity. The panels on the left represent the H1 data while the panels on the right represent the UV data. Clouds that conserve mass as they move through the Fermi Bubbles are represented in the top panels ($q = -2$) and clouds that lose mass as they move through the Fermi Bubbles are represented in the bottom panels ($q = -4$). There are significantly fewer UV FB HVC detections when compared to the number of detected H1 Galactic center clouds, giving the UV panels a less continuous appearance than the H1 panels.

We conclude from the H1 data that the most likely flow velocities for values of $q = -2$ and $q = -4$ span a range of 60–250 km s$^{-1}$ and 60–300 km s$^{-1}$, respectively, for $r < 1$ kpc, and mostly the upper portion of this range for $1 < r < 2$ kpc (i.e., red, orange, and yellow portions of the figures). The clouds detected in the UV at $1 < r < 2$ kpc have most probable velocity ranges that generally agree with those seen in the H1 data: 100–200 km s$^{-1}$ for $q = -2$ and 125 to $\sim 400$ km s$^{-1}$ for $q = -4$. The most probable velocity ranges in the UV data either accelerate or coast to 300–425 km s$^{-1}$ for $2 < r < 6.5$ kpc in both $q$ values.

We note that the high probabilities at $\sim 6.5$ kpc are driven mainly by three sight lines: RBS 1768, MS-ZNG1, and Mrk 1392. Each of these sight lines has an absolute Galactic latitude of 48°–50°, and all of their detected FB HVCs are blueshifted. It is therefore worth noting that in a more realistic geometry like that of Miller & Bregman (2016), these clouds at $\sim 6.5$ kpc would be moving too fast to be within the gamma-ray-defined Fermi Bubbles, as discussed in Section 4.1.1. Because these FB HVCs are driving the trend of acceleration and are moving too
fast to be confined within the Fermi Bubbles, it is likely that the $v_{\text{flow}}$ shown in Figure 10 at 6.5 kpc has a range lower than 300–425 km s$^{-1}$. We therefore conclude that the UV data likely favor a coasting phase within the Fermi Bubbles between 2 and 6.5 kpc.

### 4.2. Gas Phases in the Fermi Bubbles

Our UV absorption-line data constrain the thermal phase of the cool gas in the Fermi Bubbles. In principle, the gas could be in a multiphase state where the high and low ions reside in distinct volumes at different densities and temperatures, or in a single-phase state where the high and low ions are cospatial at a single density and temperature. Single-phase states could arise in several scenarios, including photoionization equilibrium, collisional ionization equilibrium, non-equilibrium photoionization, and non-equilibrium collisional ionization. In non-equilibrium collisional ionization, high-ionization states can be observed at lower temperatures than would hold under equilibrium conditions when the cooling timescale is shorter than the recombination timescale, leaving frozen-in ionization (Kafatos 1973).

Although the ionizing environment of the Fermi Bubbles could be very different from the rest of the Milky Way halo, a useful comparison sample is provided by other Galactic HVCs (away from the Galactic Center). Analysis of UV observations including the high-ion O VI, has led several groups to favor multiphase models for Galactic HVCs, in which the high ions arise in conductive interfaces or turbulent mixing layers around the cool gas cores (Sembach et al. 2003; Fox et al. 2004, 2005; Collins et al. 2005; Ganguly et al. 2005; Bordoloi et al. 2017a). In such a multiphase scenario, little or no velocity centroid offset may exist between the low ions and high ions, even though the two reside in different physical regions, but a difference in $b$ values would be expected because their thermal broadening components would be different (Börhringer and Hartquist 1987; Borkowski et al. 1990).

In the FB HVCs, the high-ion to low-ion velocity offsets allow us to test this multiphase scenario. In Table 3 we compared the average centroid velocity difference $\langle \Delta v \rangle$ between different ions (high, mid, and low). The high–low ion pairs have an offset average of 9.3 km s$^{-1}$ with a standard error of the mean of 1.2 km s$^{-1}$. The low–low ion pairs are a good comparison sample to the high–low ion pairs because we expect low ions to live with other low ions, and there is a statistically significant sample of low ions. The low–low ion pairs have an offset average of 4.0 km s$^{-1}$ with a standard error...
of the mean of 0.5 km s$^{-1}$. Even though the low–low ion pairs have an average offset that is half that of the high–low ion pairs, we note that the standard deviations of their respective $\langle \Delta v \rangle$ are $5.5$ km s$^{-1}$ and $9.4$ km s$^{-1}$. Such large standard deviations suggest that the high–low ion pairs may have similar average offsets to the low–low ion pairs. This suggests that the FB HVCs likely have a single-phase structure, conductive interfaces, or turbulent mixing layers.

Previous work with high-resolution STIS data indicates (e.g., Keeney et al. 2006; Zech et al. 2008; Savage et al. 2017) that a portion of the FB HVCs have a multiphase structure. The $b$-value distribution plot of the full Fermi Bubble sample in Figure 5 does not obviously distinguish between multiphase and single-phase FB HVCs, making such plots difficult to interpret. Individual analysis of the FB HVCs, preferably with FUSE data covering the OVI absorption and high-resolution STIS data, would be necessary to determine the phase state of the individual clouds in the full Fermi Bubble sample, a task that is beyond the scope of this survey paper.

4.3. Cooling and Recombination Timescales

The lack of trends in the ion ratios against latitude shown in Figures 8(a)–(d) and discussed in Section 3.5 could indicate that the clouds do not spend enough time in the Fermi Bubbles to cool, as suggested by K18.

B17 show that it takes FB HVCs $\sim$6–9 Myr to travel from the center of the galaxy to the top of the Fermi Bubbles. We can calculate the cooling time using

$$t_{\text{cool}} = 3kT/n\Lambda(T, Z),$$

(8)

where $k$ is the Boltzmann constant, $T$ is the initial temperature of the gas in Kelvin, $n$ is the initial density of the gas in cm$^{-3}$, and $\Lambda(T, Z)$ is the temperature- and metallicity-dependent cooling function in erg cm$^3$ s$^{-1}$ (Heckman et al. 2002; Bordoloi et al. 2017a). The clouds probed by the UV absorption lines under study have temperatures of $\sim$10$^4$–10$^5$ K. We estimate the density of the gas using the NORAD Atomic Data site.13 We also use the same density used to calculate $t_{\text{cool}}$. From these calculations, we obtain $t_{\text{cool}}$ values of 0.117 and 0.033 Myr for 10$^4$ K and 10$^5$ K, respectively. The calculated recombination timescales are broadly consistent with the cooling timescales but much shorter than the gas travel time through the Bubbles. This suggests the high ions are not experiencing frozen-in ionization, and instead may be created in situ in the flow, either by photoionization or collisional ionization. Detailed ionization modeling would be worthwhile to investigate their origin.

5. Conclusions

Using new UV spectra from HST/COS, we have studied five quasar sight lines passing at low latitude near the Galactic Center. Four of the five pass through the southern Fermi Bubble and the other passes just outside. Using this data set, we have mapped the kinematics and ion properties of the Fermi Bubble absorption components. Our results can be summarized as follows.

1. FB HVCs are detected in three of the four sight lines that pass through the Fermi Bubbles, whereas none are detected in the sight line passing outside. Combining our data with previous quasar sight lines through the Fermi Bubbles, we find that 12 out of 15 or 80% of Bubble sight lines have at least one FB HVC detected. This high covering fraction supports the interpretation that the FB HVCs trace gas physically associated with the bubbles.

2. We do not observe any asymmetries in the maximum absolute velocity of clouds between the northern and southern Fermi Bubbles. The dependence of velocity on Galactic latitude is similar in both hemispheres.

3. We compute the velocity profile of the outflowing cool gas by comparing $v_{\text{GSR}}$ with absolute latitude for the UV-absorbing and the H-emitting FB HVCs. We also model the deprojected flow velocity of the FB HVCs up to 6 kpc. We find that there is no evidence for deceleration of the outflow up to $|b| \approx 40^\circ$.

4. We note the presence of several blueshifted anomalous-velocity FB HVCs located at Galactic latitudes of $\pm 30^\circ$. The geometry of the Fermi Bubbles would require the projected LSR velocities of these FB HVCs to be significantly lower than is measured because they would be moving perpendicular to the line of sight at latitudes of $45^\circ$. This indicates that they are likely located outside of the Fermi Bubbles. These anomalous-velocity FB HVCs could be the remnants of a past Galactic center outburst.

5. The incidence of FB HVCs (number of components per sight line) is high at $|b| < 10^\circ$ and rapidly decreases until $|b| \approx 40^\circ$–$50^\circ$, where it rises again as the upper boundaries of the Fermi Bubbles are intersected. The decrease can be understood as the FB HVCs decreasing in volume density as they flow up into the halo. The incidence of FB HVCs is relatively constant with longitude.

13 Nahar OSU Radiative Atomic Data website: https://norad.astronomy.osu.edu.
6. The velocity centroid offsets from high–low ion pairs and low–low ion pairs have similar distributions, as we confirm using a two-sided K-S test. Because the high–low ion pairs have the same distribution as the low–low ion pairs (which are expected to live with each other), this result is evidence for a single-phase structure, conductive interfaces, or turbulent mixing layers.

7. The FB HVCs have \( b \) values with similar distributions for the high (Si IV and C IV) and low ions (Si II, C II, and Si III), as we confirm using two-sided KS tests. In both cases the mean \( b \) value is \( \sim 22 \, \text{km s}^{-1} \).

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Facility: HST (COS) and GBT.

Software: VPFT, IDL, R, and Python.

Appendix A

HST/COS Absorption-line Spectra of Five New Sight Lines

In Figure A1 we present the UV data for four of the five new quasar sight lines. This figure is a continuation of Figure 2. We shade each high-velocity absorption component that is associated with an FB HVC detected in pink or blue for redshifted and blueshifted components, respectively. We also include tickmarks in each panel to indicate the velocity of detected FB HVCs. We present all of the identified FB high-velocity absorption components from the five new sight lines in Table A1. This table lists each absorption component’s velocity centroid, \( b \) value, column density, and line ID. The initial groupings of gas clouds (based on the visual alignment of their velocity centroids) are separated by horizontal lines. Each absorption feature determined to be part of the same cloud is assigned a number, as indicated in the Line ID column of Table A1. Upper-case letters in the Line ID column of Table A1 indicate that the absorption is not matched to any other absorbers (NM), or matched to some, but not all, absorbers in a high-velocity cloud (N). It is worth noting that two of the three absorption features that are labeled N have low \( \sigma \) values.
Figure A1. Continued from Figure 2.
Figure A1. (Continued.)
**Table A1**
High-velocity Absorption-line Parameters

| Sight Line     | Ion   | \(v_{\text{LSR}}\) (km s\(^{-1}\)) \(^a\) | ±  | Error including Systemic Error | b Value (km s\(^{-1}\)) ±  | \(\log N\) ±  | \(\sigma\) | Line ID \(^b\) |
|----------------|-------|---------------------------------|----|--------------------------------|--------------------------|-------------|--------|--------------|
| UVQS J185302–415839 | O I  | −125.4                          | 3.8 | 8.4                           | 16.7                     | 5.2          | 13.70  | 0.12          | 4.14 ± 3.14 | 1 |
|                | C II | −120.2                          | 2.1 | 7.8                           | 33.0                     | 3.5          | 14.10  | 0.04          | 11.33 ± 10.33 | 1 |
|                | Al II| −122.6                          | 8.5 | 11.3                          | 38.2                     | 12.5        | 12.41  | 0.12          | 4.16 ± 3.16 | 1 |
|                | Si II| −117.4                          | 1.4 | 7.6                           | 31.8                     | 2.0          | 13.11  | 0.02          | 18.42 ± 17.42 | 1 |
|                | Si III| −125.7                         | 1.6 | 7.7                           | 23.8                     | 2.0          | 12.93  | 0.05          | 9.79 ± 8.79 | 1 |
|                | C IV | −122.9                          | 10.0 | 12.5                          | 52.7                     | 11.9        | 13.66  | 0.10          | 4.94 ± 3.94 | 1 |
|                | Si IV| −118.9                          | 2.0 | 7.8                           | 14.5                     | 2.7          | 12.67  | 0.07          | 6.45 ± 5.45 | 1 |
|                | C II | −207.4                          | 8.7 | 11.5                          | 41.2                     | 15.1        | 13.49  | 0.13          | 3.81 ± 2.81 | 2 |
|                | Si III| −197.4                      | 3.2 | 8.1                           | 25.4                     | 4.7          | 12.33  | 0.07          | 6.96 ± 5.96 | 2 |
|                | O I  | 106.2                          | 3.0 | 8.1                           | 9.5                      | 4.1          | 13.44  | 0.17          | 3.14 ± 2.14 | N |
|                | C II | 129.2                          | 2.4 | 7.9                           | 30.1                     | 3.0          | 14.05  | 0.04          | 10.24 ± 10.24 | 3 |
|                | Al II| 136.9                          | 14.5 | 16.3                          | 67.1                     | 20.2        | 12.74  | 0.11          | 4.37 ± 3.37 | 3 |
|                | Si II| 117.9                          | 2.3 | 7.8                           | 38.2                     | 3.2          | 13.09  | 0.03          | 13.61 ± 13.61 | 3 |
|                | Si III| 148.2                          | 3.2 | 8.2                           | 30.7                     | 3.8          | 12.80  | 0.06          | 7.43 ± 6.43 | N |
|                | C IV | 145.2                          | 6.8 | 10.1                          | 32.8                     | 10.4        | 13.15  | 0.11          | 4.35 ± 3.35 | 3 |
|                | Si IV| 137.8                          | 7.2 | 10.4                          | 29.6                     | 10.0        | 12.52  | 0.13          | 3.91 ± 2.91 | 3 |
|                | Si II| 250.5                          | 6.9 | 10.2                          | 51.6                     | 10.2        | 12.51  | 0.07          | 5.33 ± 5.33 | 4 |
|                | Si III| 245.5                       | 4.2 | 8.6                           | 28.3                     | 6.0         | 12.29  | 0.08          | 6.01 ± 5.01 | 4 |
| UVQS J185649–544229 | Si III| 169.0                          | 15.3 | 17.0                          | 39.1                     | 22.8        | 12.35  | 0.21          | 2.58 ± 1.58 | NM |
| UVQS J191928–295808 | Si III| 229.0                          | 2.3 | 8.0                           | 28.7                     | 3.8          | 12.56  | 0.05          | 9.12 ± 8.12 | 5 \(^d\) |
|                | Si II| 279.3                          | 11.5 | 13.7                          | 34.8                     | 16.3        | 12.08  | 0.18          | 3.01 ± 2.01 | N |
|                | C IV | 239.7                          | 6.3 | 9.8                           | 22.0                     | 8.7          | 12.90  | 0.15          | 3.40 ± 2.40 | 5 \(^d\) |
| UVQS J193819–432646 | C II | −111.1                          | 3.3 | 8.2                           | 24.0                     | 4.7          | 13.30  | 0.07          | 5.31 ± 5.31 | 6 |
|                | Si III| −109.7                        | 1.8 | 7.7                           | 22.0                     | 2.6          | 12.62  | 0.05          | 10.09 ± 10.09 | 6 |
|                | Si IV| −92.3                          | 6.0 | 9.6                           | 39.7                     | 8.9          | 12.88  | 0.08          | 5.78 ± 4.78 | 6 |

**Notes.** High-velocity absorption features from the five new sight lines. Absorption features are grouped by their centroid velocities.

\(^a\) \(v_{\text{LSR}}\) is the absorption centroid in the LSR frame of the absorption feature.

\(^b\) The velocity centroid error has been added to the zero-point error in quadrature to obtain a total velocity centroid error.

\(^c\) Each absorption feature is separated into clouds according to methods described in Section 2.3. The label in the cloud ID column shows these separate clouds grouped together as indicated by numbers. “N” indicates that an absorption feature was matched by some, but not all lines in a cloud. “NM” indicates that no matching absorber or cloud was found.

\(^d\) This FB HVC has a significance of \(\geq 8.1\sigma\) in Si III and \(\geq 2.4\sigma\) in Si II. We chose to keep this FB HVC in our analysis because Si III has a large \(f\) value; therefore, we would expect any FB HVC detection to be strongest in Si III.

### Appendix B

**Velocity Centroid Offset Calculations versus Cloud-matching Process**

The cloud-matching process described in detail in Section 2.3 assumes that the absorption features in two ions should have matching velocity centroids to within 3\(\sigma\) if they are part of the same FB HVC. However, if the ionization mechanism of the gas produces a large velocity offset between the low and high ions, then by including only the matched ions, we could have introduced a bias toward low-\(\Delta v\) values contributing to calculations presented in Table 3.

To address this concern we recalculated the \(\langle \Delta v \rangle\) values for each ion pair in the full FB sample for several situations: all components (matched and unmatched), all matched components on the same grating, and all components (matched and unmatched) on the same grating. The calculations of \(\langle \Delta v \rangle\) on the same grating ensure that \(\langle \Delta v \rangle\) is not affected by the zero-point offset between the gratings. These cases have been added to the calculations of \(\langle \Delta v \rangle\) for matched components in Table B1.

In each case (matched, all components, matched same grating, and all components same grating) the \(\langle \Delta v \rangle\) values stay relatively constant for the ion pair types. We note that pairs including high ions have \(\langle \Delta v \rangle\) values that are slightly higher when unmatched components are included; however, these differences are small and within the errors. When only ion pairs in the same grating are accounted for, we do see a slight drop in several of the \(\langle \Delta v \rangle\) values for pairs including low ions, with the most significant decrease in \(\langle \Delta v \rangle\) values being in the high–low ion pairs. We note that none of these changes are within a 3\(\sigma\) significance. This demonstrates that our 3\(\sigma\) cutoff has not biased the centroid offset results and that the zero-point offset is also not affecting the centroid offset results.
Table B1
Velocity Centroid Offsets

| Ion Pair        | \( \Delta v \) (\( km \ s^{-1} \)) | Standard Error of the Mean (\( km \ s^{-1} \)) | Standard Deviation (\( km \ s^{-1} \)) | Number of Pairs |
|-----------------|------------------------------------|-----------------------------------------------|----------------------------------------|-----------------|
| Matched Components |                                   |                                               |                                       |                  |
| High–Low      | 9.3                                | 1.2                                           | 9.4                                    | 64              |
| High–Mid      | 7.8                                | 1.7                                           | 7.8                                    | 22              |
| Mid–Low       | 8.0                                | 1.1                                           | 7.0                                    | 43              |
| Low–Low       | 4.0                                | 0.5                                           | 5.5                                    | 146             |
| High–High     | 11.0                               | 3.2                                           | 12.6                                   | 16              |
| All Components |                                   |                                               |                                       |                  |
| High–Low      | 10.8                               | 1.3                                           | 11.0                                   | 75              |
| High–Mid      | 8.5                                | 1.7                                           | 8.2                                    | 23              |
| Mid–Low       | 9.9                                | 1.5                                           | 10.4                                   | 47              |
| Low–Low       | 4.2                                | 0.4                                           | 5.6                                    | 154             |
| High–High     | 13.9                               | 4.1                                           | 17.1                                   | 17              |
| Matched Components; Same Grating | |                                               |                                       |                  |
| High–Low      | 6.3                                | 1.4                                           | 6.3                                    | 20              |
| High–Mid      | 8.3                                | 2.4                                           | 8.4                                    | 12              |
| Mid–Low       | 5.6                                | 1.3                                           | 5.7                                    | 18              |
| Low–Low       | 2.7                                | 0.9                                           | 3.3                                    | 14              |
| High–High     | ...                                | ...                                           | ...                                    | 0               |
| All Components; Same Grating | |                                               |                                       |                  |
| High–Low      | 8.4                                | 1.6                                           | 8.2                                    | 27              |
| High–Mid      | 9.4                                | 2.5                                           | 9.0                                    | 13              |
| Mid–Low       | 8.2                                | 2.1                                           | 9.8                                    | 21              |
| Low–Low       | 4.5                                | 1.2                                           | 5.4                                    | 21              |
| High–High     | 33.5                               | ...                                           | ...                                    | 1               |

Note. This table shows the mean velocity centroid offset, its standard error, and the velocity centroid offset standard deviation for various ion pairs, for different subsamples of absorption.

Appendix C
Derivation of the Fermi Bubble Cone Modeling Geometry

Interpreting the velocity profile of the Fermi Bubbles is difficult due to projection effects and distance ambiguities. Using a conic-geometry model for the Fermi Bubbles, the HI Galactic center outflow data, and the UV FB HVC data, we have modeled the probabilistic deprojected flow velocities within the Fermi Bubbles. Below we derive the geometry used for calculating the differential probability in Equation (7).

The shapes of the gamma-ray emission lobes shown in Figure 1 indicate that the northern and southern Fermi Bubbles are approximately symmetric about the Galactic plane. Thus, we treat results for negative latitudes in the same manner as for positive ones. We also propose that the origin of the clouds is at or extremely close to the Galactic center. This statement is supported by the 21 cm HI data of Di Teodoro et al. (2018) which probes the low-latitude regions of the Galactic center (\( 3° \leq \theta \leq 10° \)). The FB HVCs detected in Di Teodoro et al. (2018) show a lack of systematic velocity differences between negative and positive Galactic longitudes and are therefore not participating in Galactic rotation. Di Teodoro et al. (2018) conclude that the observed FB HVCs are likely participating in an outflow originating from the Galactic center. While this is an easy assumption to implement, in the development of equations that follow, we will retain a parameter, \( z \), which represents the offset of a virtual vertex of a cone from the plane of the Galaxy. As long as we do not violate the constraint of seeing no signature of rotation, a small value for \( z \) may be permissible for representing an outflow from a disk of active stars surrounding the Galactic center.

We now envision that clouds are launched uniformly over all solid angles inside a cone with an opening half-angle, \( \alpha_{\text{max}} \). The clouds detected by Di Teodoro et al. (2018) indicate that \( \alpha_{\text{max}} \) could be as large as \( 70° \) (assuming that \( z = 0 \)), a finding consistent with the lack of HI shown in Figure 2 of Lockman & McClure-Griffiths (2016).

Drawing upon a development of equations in Sections 5.2 and 5.3 of Bordoloi et al. (2017b),\(^\text{14}\) we state that the distance from the vertex to a spot on the surface of any cone within the Fermi Bubbles with a half-angle, \( \alpha \), is given by Equation (5):

\[
r = \frac{\rho \sin b + z}{\cos \alpha}.
\]

In Figure C1 we present the geometry and parameters used in these derivations.

In Equation (5), the distance \( \rho \) of a cloud to an observer located at a distance of \( R = 8.3 \) kpc from the Galactic center is given by one of the solutions to the quadratic equation:

\[
A \rho^2 + B \rho + C = 0,
\]

where

\[
A = \frac{\sin^2 b}{\cos^2 \alpha} - 1,
\]

\[
B = \frac{2z \sin b}{\cos^2 \alpha} + 2R \cos l \cos b - 2z \sin b,
\]

\[
C = \left( \frac{1}{\cos \alpha} - 1 \right) z^2 - R^2.
\]

The two roots to Equation (C1) express the distances to the near and far sides of the cone intercepted by a sight line with the coordinates \( b \) and \( l \). If \( B^2 - 4AC < 0 \), \( \alpha \) is so small that there is no solution because the sight line misses the cone.

From our vantage point, a parcel of gas moving radially along the surface of a cone within the Fermi Bubbles at an outward velocity, \( v_{\text{flow}} \), will be observed at a reduced velocity \( v_{\text{GSR}} = v_{\text{flow}} \cos \beta \), where \( \beta \) is the angle between the flow direction and the obsering direction. The projection of one of these directions on the other is given by

\[
\cos \beta = \frac{\rho - R \cos l \cos b + z \sin b}{r}.
\]

For small values of \( r \) and large values of \( \alpha \) on the near side of the cone, \( \cos \beta \) can revert to negative values and cause a sign reversal between \( v_{\text{GSR}} \) and \( v_{\text{flow}} \). For this reason, we must accept the possibility that observations could possibly represent outflowing motions (\( v_{\text{GSR}} < 0 \)) or inflalling high-velocity clouds that are unrelated to the outflow (\( v_{\text{GSR}} > 0 \)). In our analysis, we treat every high-velocity cloud as if it were relevant to the outflow and ignore the unavoidable prospect that some of them are contaminating our sample, because they may belong to the population of HVCs seen elsewhere at high Galactic latitudes.

\(^{14}\) We have made some changes in notation to the equations in Bordoloi et al. (2017b): their \( \Theta \) is equivalent to our \( \rho \) and their OA/2 is equivalent to our \( \alpha \).
Figure C1. Cartoon of the conic-geometry Fermi Bubble model. The dashed–dotted line is used to show the parameter \( z \); it represents the Galactic plane if the outflow where to start a distance \( z \) off of the Galactic plane.

Using the geometry described above, we calculate a differential probability, \( \Delta P \), per unit change in \( \nu_{\text{flow}} \) for relevant values of \( \nu_{\text{flow}} \) and \( r \) in Section 4.1.2. \( \Delta P \) can be calculated for any differential element \( \Delta \alpha \) between the minimum \( \alpha \) for a sight line to penetrate the cone and \( \alpha_{\text{max}} \).

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