Diverse metallicities of Fermi bubble clouds indicate dual origins in the disk and halo

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The Galactic Centre is surrounded by two giant plasma lobes known as the Fermi bubbles, extending ~10 kpc both above and below the Galactic plane. Spectroscopic observations of Fermi bubble directions at radio, ultraviolet and optical wavelengths have detected multi-phase gas clouds thought to be embedded within the bubbles, referred to as Fermi bubble high-velocity clouds (FB HVCs). Although these clouds have kinematics that can be modelled by a biconical nuclear wind launched from the Galactic Centre, their exact origin is unknown because there has so far been little information on their heavy metal abundances (metallicities). Here we show that FB HVCs have a wide range of metallicities from <20% of solar to ~320% of solar, based on a metallicity survey of twelve FB HVCs. These metallicities challenge the previously accepted tenet that all FB HVCs are launched from the Galactic Centre into the Fermi bubbles with solar or supersolar metallicities. Instead, we suggest that FB HVCs originate in both the Milky Way’s disk and halo. As such, some of these clouds may characterize the circumgalactic medium that the Fermi bubbles expand into, rather than material carried outwards by the nuclear wind, changing the canonical picture of FB HVCs. More broadly, these results reveal that nuclear outflows from spiral galaxies can operate by sweeping up gas in their haloes while simultaneously removing gas from their disks.

Nuclear outflows are an important source of feedback in spiral galaxies. In the Milky Way, evidence of a nuclear outflow is provided by two large plasma bubbles launched from the Galactic Centre into the halo, known as the Fermi bubbles. Simulations and observations suggest that the Fermi bubbles are probably the result of Galactic nuclear activity from Sagittarius A* (refs. 1–5) and that they may have formed during a Seyfert flare event ~3.5 Myr ago that ionized the Magellanic Stream 6. However, star formation in the Galactic Centre cannot be ruled out as a partial contributor to the origin and growth of the bubbles 7,8. Their large angular extent (±55° in latitude and ±20° in longitude) allows us to resolve a nuclear outflow and study its effect on the baryons of a large spiral galaxy in great detail.

The bubbles have been detected across the electromagnetic spectrum in gamma-rays, microwaves, polarized radio emission and X-rays 9–11. Spectroscopic studies on UV metal line absorption and atomic hydrogen (H1) and molecular emission have revealed populations of cool gas clouds assumed to be embedded within the bubbles 12–24. These Fermi bubble high-velocity clouds (FB HVCs) are identified by their projected location towards the gamma-ray-defined bubbles and their velocities, which cannot be accounted for by Galactic rotation (typically exceeding absolute velocities of ~90 km s⁻¹). FB HVCs are thought to be associated with the bubbles because their UV absorption covering fraction (80%) far exceeds that of HVCs directly outside the Fermi bubbles that are similarly not co-rotating with the Milky Way disk (28%) 25.

Previously, all FB HVCs have been assumed to originate in the disk of the Milky Way, becoming entrained in the Fermi bubbles and travelling to higher Galactic latitudes (l) 16,17,20. FB HVCs detected in H1 radio surveys are close to the Milky Way disk’s central H1 cavity 25 (absolute Galactic longitude |l| < 10°) and have kinematics that can be successfully modelled with a biconical outflow. As such, they are thought to originate in the disk of the Milky Way. However, UV-detected FB HVCs seen at up to l = 55° (a projected distance of ~10 kpc from the disk) are not so clearly connected to the Milky Way disk and have never had their origin confirmed. Simulations have shown that it is difficult to accelerate a cool cloud in a galactic outflow without destroying it 26–29, as the cloud has to survive the shock and shear of the outflow. Instead, some of the high-latitude UV-detected FB HVCs may be halo clouds that existed before the formation of the bubbles.

Metallicity measurements (heavy metal abundances) from H1 and UV data can directly constrain the origin of the FB HVCs, because clouds driven into the bubbles from the Galactic disk are expected to show solar (or supersolar) metallicities, whereas halo clouds should have subsolar metallicities 30–32. We conducted a metallicity survey of FB HVCs by combining measurements of three newly detected FB HVCs with measurements of nine clouds categorized as FB HVCs in the literature 17,18,20,33,34. We calculated new ionization corrections and metallicities for the literature sample in all but one case (see the Methods and Extended Data Fig. 1 for more details). The three newly detected FB HVCs each have UV spectra from the Cosmic Origins Spectrograph on the Hubble Space Telescope (HST/COS) as well as H1 maps and deep single-pointing H1 spectra from the Green Bank Telescope (GBT). In Fig. 1 we show the location of each sight line on a gamma-ray map of the Fermi bubbles, including H1 maps of the FB HVCs with detected H1 emission when available. The H1 maps show the environment, morphology and spatial size of each cloud. The FB HVC towards 1H1613-097 is a centrally concentrated, compact structure (<0.4° in size) whereas the new FB HVCs J1919-2958 and J1938-4326 are tenuous and diffuse in H1. These H1 maps were used to quantify the

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Fig. 1 | Map of metallicity measurements. Map of the Fermi Bubbles with UV sight lines from this sample plotted on top of an adapted 3–10 GeV residual intensity Fermi gamma-ray map\(^\text{12}\) (greyyscale; \(\sim 5 \times 10^{-1} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}\)). Yellow, green and blue symbols correspond to clouds with metallicities of \(\leq 21\%\), \(30\% \leq Z \leq 59\%\) and \(> 85\%\) of solar (solar metallicity, \(Z_\odot\)), respectively. Circles represent background quasars, stars represent background stellar sight lines and triangles represent lower-limit metallicity measurements from background quasars. We include the GBT H\(_i\) maps (when available) plotted to approximately the same angular scale for the sight lines. The circles in the bottom left of each subpanel indicate the 21 cm beam size and the white X indicates the location of the UV sight line. The colour scale used for the H\(_i\) maps represents the H\(_i\) column densities. The maps were made by integrating over velocities of \(-201\) to \(-150 \text{ km s}^{-1}\) for J1613-097, \(-123\) to \(-56 \text{ km s}^{-1}\) for J1938-4326 and 65 to 131 \text{ km s}^{-1} for J1919-2958. The units are \(N \times 10^{18} \text{ cm}^{-2}\) where \(N = 1, 3\), and 5 for J1613-097, J1938-4326 and J1919-2958, respectively. Figure adapted with permission from ref.\(^{12}, \text{IOP}\).

Table 1 | Sample and metallicity measurements

| Reference | Sight line | \(l\) (°) | \(b\) (°) | Spectral type | \(X\) | \(v_{\text{UV}}\text{ (km s}^{-1}\) | \(Z\) \((Z_\odot)\) |
|-----------|------------|-----------|-----------|--------------|-------|----------------|----------------|
| This work | J1919-2958 | 8.18      | -18.77    | Quasar       | O\(_i\) | 97.8 ± 7.7   | [0.30, 0.54]  |
| This work | J1938-4326 | 355.47    | -26.41    | Quasar       | C\(_{\text{II}}\) | -1071±8.2  | [0.010, 0.10] |
| 17        | 1H1613-097 | 3.53      | 28.46     | Quasar       | O\(_i\) | -163 ± 1     | 0.19 ± 0.10   |
| 18        | LS 4825-1  | 1.67      | -6.63     | B1 Ib-II     | O\(_i\) | 92.1 ± 0.8   | ≥ 0.21        |
| 18        | LS 4825-2  | 1.67      | -6.63     | B1 Ib-II     | S\(_{\text{II}}\) | -78 ± 1     | 0.85 ± 0.41   |
| 34        | M5-ZNG1    | 3.86      | 46.79     | sdO          | O\(_i\) | -124 ± 7     | 3.2 ± 0.8     |
| 33        | PKS 2005-489 | 350.37    | -32.60    | Quasar       | ...  | 168 ± 10     | ≤ 0.20        |
| This work | J1853-4158 | 354.36    | -18.04    | Quasar       | O\(_i\) | -120.2 ± 8.4 | ≥ 0.59        |
| 17        | J1509-0702 | 7.80      | 51.61     | Quasar       | O\(_i\) | -115.2 ± 7.8 | ≥ 0.59        |
| 18        | LS 4825-3  | 1.67      | -6.63     | B1 Ib-II     | O\(_i\) | -205 ± 2     | ≥ 0.44        |
| 18        | LS 4825-4  | 1.67      | -6.63     | B1 Ib-II     | O\(_i\) | -155 ± 1     | ≥ 2.6         |
| 17        | PG 1522+101 | 14.89     | 50.12     | Quasar       | O\(_i\) | -99.8 ± 8.3  | ≥ 0.30        |

The type of each background source is listed as quasar or the stellar spectral type. \(X\) represents the ion used for metallicity calculations. The UV Voigt fit local standard of rest (LSR) velocity centroid is \(v_{\text{UV}}\). \(Z\) represents the corrected elemental abundances in linear form (see Methods and Extended Data Fig. 1-5 for further details of the Methods). The MS-ZNG1 measurement applies to two absorption components that are blended in H\(_i\). We treated them as a single cloud because only an average metallicity measurement was possible. PKS 2005-489’s metallicity measurement is a literature measurement made by comparing UV ion and Lyman measurements to other Milky Way HVCs; as such, the ion used for PKS 2005-489’s metallicity is shown as blank or ‘...’. J1938-4326’s metallicity limit includes an estimate for dust depletion and is a range due to multiple H\(_i\) measurements; as explained in detail in Supplementary Section 1.

Of all the absorption lines covered in the COS dataset (observed with the G130M and G160M gratings), O\(_i\) \(\lambda\)1302 and S\(_{\text{II}}\) \(\lambda\)1250, \(\lambda\)1253, \(\lambda\)1259 are the most useful for interstellar metallicity measurements because their ionization corrections are small at large H\(_i\) column densities (log \(N_{\text{HI}}\) \(\geq 18.5\) and 19.5 for O\(_i\) and S\(_{\text{II}}\), respectively; \(N_{\text{HI}}\) in \(\text{cm}^{-2}\))\(^{17,20}\). Moreover, oxygen does not have high levels of dust depletion and even though sulfur has been shown to sporadically deplete (up to 1 dex in the dustiest clouds)\(^{36}\), sulfur is not typically thought to strongly deplete onto dust\(^{38}\). We therefore used these two ions for metallicity measurements. We selected our sample to contain all known FB HVCs with detected O\(_i\) or S\(_{\text{II}}\) absorption and associated H\(_i\) detections. Another measurement included in our sample is a FB HVC towards J1938-4326, which has a C\(_{\text{II}}\) \(\lambda\)1334 detection and an associated H\(_i\) detection. The O\(_i\) absorption of J1938-4326 is blended with the background quasar’s intrinsic Si\(_{\text{II}}\) absorption and it has no detected Si\(_{\text{II}}\) absorption. Instead, we used C\(_{\text{II}}\) \(\lambda\)1334 for the metallicity tracer in this cloud as carbon is only weakly depleted\(^{35}\),
although the ionization correction is substantial. We also incorporated PKS 2005-489’s metallicity measurement from the literature into the sample\(^1\). Neither O i nor S ii detections exist for PKS 2005-489. Instead, its metallicity measurement was made by comparing its H i column and detected ion abundances to those of Milky Way halo gas clouds with measured metallicities; therefore, all ions detected in this sight line were used to determine the FB HVC’s metallicity\(^3\). We also included FB HVCs with distinct O i detections and H i column density upper limits in our sample, providing lower-limit metallicity measurements. We only used O i \(\lambda 1302\) detections with H i upper limits because (unlike other elements) oxygen has small ionization corrections for log \(N_{\text{HI}}\) \(\geq 18.5\) (ref. \(^1\)). In Fig. 2 we plot the O i or C ii absorption profiles and H i single-pointing emission profile for the three newly detected FB HVCs in our sample.

We found that four FB HVCs in our sample have low metallicities of \(\leq 21\%\) of solar (one of which is a lower limit), five have metallicities between \(\geq 30\%\) and \(\geq 59\%\) of solar, and three have near-solar or supersolar metallicities of \(\geq 85\%\) of solar (see Table 1). The low metallicities (\(\approx 20\%\) of solar) are indicative of Galactic halo clouds\(^3\) and similar to that measured for the X-ray component of the Fermi bubbles using Suzaku X-ray data\(^7\). By comparison, disk clouds that come from the Galactic Centre should have solar or supersolar metallicities\(^3\)\(^,\)\(^8\)

Only one of our sight lines, LS 4825, probes the low-latitude portion of the Fermi bubbles, close to the disk and central H i cavity (\(b = -6.63^\circ\)) where FB HVCs are expected to have near-solar metallicities. LS 4825 has four FB HVCs that have distances between 7 and 21 kpc as shown by their absence in absorption spectra towards a closely aligned foreground star\(^1\). We found that the FB HVCs towards LS 4825 (LS 4825-1, -2, -3, -4) have metallicities of \(\geq 21\%\), \(85 \pm 15\%\) \(\geq 44\%\) and \(\geq 260\%\) of solar. Two of these metallicities are near solar (LS 4825-2 and -4). Of the other two metallicity measurements, LS 4825-1 has an uncertain H i measurement due to a complex H i emission spectrum and potential narrow O i absorption line (see the Methods for details), and LS 4825-3 has a measurement based on an H i upper limit. It is therefore possible that these two FB HVCs have higher metallicities than reported.

As explained in detail in the Methods, the metallicity measurements of the new FB HVCs were robust against beam-smearing effects that result from combining pencil-beam UV data with finite-beam radio data. Furthermore, we derived the time-dependent ionization corrections for the FB HVCs and found that a Galactic Centre Seyfert flare event 3.5 Myr ago does not have a significant effect on the clouds’ ionization corrections\(^5\)\(^,\)\(^6\) (see Methods and Extended Data Figs. 6 and 7). Neither of these effects change the result that the FB HVCs have metallicities ranging from \(< 20\%\) to \(320\%\) of solar. These results challenge the previously accepted picture that all FB HVCs were driven out from the Galactic Centre with solar or even supersolar metallicities.

### Fig. 2 | UV absorption and H i emission profiles used for metallicity measurements

H i emission line (top) and UV absorption line (bottom) profiles used to calculate metallicities for each new sight line. Voigt fits to the UV components of each FB HVC are plotted on top of the data in orange (see Extended Data Fig. 2). The full fit to all UV absorption components is plotted in green\(^1\). The velocity centroid of each fit is denoted by the vertical dashed lines and the horizontal dotted lines represent the baseline and continuum level for both the H i and UV spectra, respectively. No H i emission associated with J1853-4158’s FB HVC was detected at the sensitivity of the data. J1919-2958’s H i column limits were computed using the velocity range indicated by the grey shaded region after flipping the spectrum around its peak emission and subtracting the resulting spectrum from the original, as discussed in detail in the Methods (see Extended Data Fig. 3). J1938-4326’s Gaussian fit to the FB HVC H i emission is indicated by a red line (see Extended Data Fig. 2). \(T_B\) is brightness temperature and \(v_{\text{LSR}}\) is local standard of rest velocity.
One potential explanation for the subsolar metallicities observed in many of the FB HVCs is that the clouds originate in the Milky Way disk with solar metallicity and then become diluted to subsolar metallicities via metal mixing as they travel through the Fermi bubbles to higher latitudes. However, as we discuss below, we found that metal mixing cannot explain FB HVC metallicities of \( Z \lesssim 20\% \) of solar. Mixing can occur when cold gas clouds traveling through a hot ambient medium leave a wake of stripped gas behind them. The stripped gas then mixes with the ambient gas, reducing its temperature enough to allow condensation of the hot medium onto the stripped cold cloudlets, resulting in a cloud with a metallicity between the cold cloudlets and hot plasma\(^{29,41}\). In this scenario, FB HVCs originating from the Milky Way's disk with solar (or supersolar) metallicities would need to be mixed down to subsolar metallicities (\( \lesssim 20\% \) in some cases) by low-metallicity hot plasma. The metallicity of the Fermi bubbles' plasma is difficult to determine. The Fermi bubble X-ray component has a measured metallicity of \( \sim 20\% \) of solar\(^{23} \); however, these measurements were based on limited photon statistics and are not necessarily indicative of the metallicity in the gamma-ray component of the bubbles. The gamma-ray-emitting plasma is probably enriched with metals from the Milky Way's ionized interstellar medium and from the shocked hot Milky Way halo component as the bubbles expand into the halo. The interstellar medium has near-solar metallicities and the hot halo has a relatively high metallicity of \( \sim 60\% \) of solar\(^{30,42,43} \), so neither source is expected to reduce the Fermi bubble plasma's metallicity to \( \lesssim 20\% \) of solar. Moreover, current models of cold clouds moving through the Milky Way halo find that it takes tens of million years for significant portions of the ambient hot halo to condense onto the cloudlets\(^{41,43} \); this timescale would be even longer in the Fermi bubbles, which have temperatures approximately twice as hot as the Milky Way halo and therefore take longer to cool and condense\(^{28} \). As such, given that the Fermi bubbles are only 3–6 Myr old (refs.\(^{23} \)), cold cloudlets would not have sufficient time to condense a significant amount of the plasma, leaving them with relatively unchanged metallicities. Considering all of these effects, we concluded that it is unlikely that mixing can explain FB HVCs with \( Z \lesssim 20\% \) of solar.

We suggest an alternative explanation. FB HVCs have a large range in metallicities because they have two origins: the Milky Way's disk and its halo. In this picture, one population of FB HVCs is composed of the low-latitude FB HVCs that originate in the disk of the Milky Way and are accelerated away from the Galactic Centre by the same mechanism that created the Fermi bubbles. These cool gas clouds could be accelerated by the hot gas flow and eventually become eroded as their mass transfers from a cool to hot phase\(^{29,46} \). The remnants of many of these clouds probably become too dispersed, ionized and hot to be seen in the UV as they move to higher latitudes. The second population of FB HVCs is composed of pre-existing halo clouds that are shocked and accelerated as the Fermi bubbles expand into the halo. As such, they represent the medium into which the Fermi bubbles expand, rather than material carried out by the Milky Way's nuclear outflow.

The division between the disk and halo clouds does not occur at a single latitude, as shown by the FB HVC towards M5–ZNG1 (high metallicity at a high latitude of 47\(^{\circ} \)). This outlier suggests that the outflow is complex and that some disk clouds may be able to survive to higher latitudes in the bubbles. Although it is not clear how these clouds survive the shock and shear of the Fermi bubbles, a range of ideas have been suggested from internal magnetic fields suppressing the destruction of the clouds to radiative cooling increasing a cloud's lifetime in a hot outflow\(^{26,29} \). In any case, the UV-detected FB HVCs reported in this Article have a large range of metallicities from \( < 20\% \) of solar to \( > 320\% \) of solar, a result that requires a revision to the canonical picture of FB HVCs and indicates that biconical outflow models need to be refined to account for the clouds' dual origins.

Our results on the metallicity and origin of FB HVCs reveal the properties of a nuclear outflow in more detail than is possible in any other spiral galaxy. As such, the Fermi bubbles serve as an important analogue for extragalactic nuclear outflows, which can typically only be studied with one-dimensional down-the-barrel pointings. In general, galactic outflows and outward-moving shocks are thought to prevent inflowing cool gas clouds from reaching the disk of a galaxy, thus quenching the star-formation process\(^{42} \). Although the Fermi Bubbles are not likely to be strong enough to quench the Milky Way\(^{48,49} \), they remain important for understanding how nuclear outflows entrain and sweep up cool halo gas, thus circulating matter between the disks and haloes of galaxies.

### Methods

**Sample.** Our full sample consisted of nine sight lines passing through the Fermi bubbles. Three of the nine sight lines were new quasar sight lines\(^{3} \) and the other six were taken from the literature\(^{12,43,44} \). We had UV O I or Si II absorption and H I emission measurements for five FB HVCs. We also had O I absorption measurements and measured the H I limits for five more FB HVCs. We had one FB HVC with no O I absorption and H I emission measurements and another FB HVC with a UV-based literature metallicity measurement. The UV data for nine sight lines had previously been calibrated and analysed\(^{23,43,44,45} \). We took new measurements for the UV absorption or H I emission associated with three literature FB HVCs (J1509-0702, PG 1522+101 and LS 4825; see the ‘UV ion and H I column densities of the literature sample’ section). Most of the FB HVCs in our sample had not had their metallicities calculated and many of the metallicity calculations in the literature do not include an ionization correction—an important correction for clouds that are exposed to the Galactic, extragalactic and Seyfert flare ionizing radiation fields, in addition to cosmic rays. Table 1 lists information for each sight line and associated cloud(s).

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The H I column density (in cm⁻²) for J1919-2958 and J1938-4326 was calculated using the standard relation:

\[
N_{\text{H I}} = 1.823 \times 10^{18} \int T_B(v) \, dv
\]

where \(T_B(v)\) is the velocity-dependent brightness temperature in K and \(v\) is in km s⁻¹. For the Gaussian fit to J1938-4326's FB HVC, the integral reduces to \(\int f(v) \, dv = 1.0648 \, \text{FWHM} \), where \(\text{FWHM}\) is the full width of the Gaussian at half-maximum in km s⁻¹. A check on J1938-4326's H I column density measurement was conducted in Supplementary Section 2 using the flip-and-subtract method described above. For J1853-4158, we calculated the H I column upper limit as that given by three times the root mean square over the column density measurement was conducted in Supplementary Section 2 using deviation of both the H I velocity centroids and FWHM of fits in Supplementary Section 3 (see also Supplementary Fig. 1).

We present the GBT H I moment zero field for J1919-2958 and 1938-4326 in Fig. 1 (approximately 1.0° × 1.0° for J1919-2958 and 0.5° × 0.5° for J1938-4326). We did not include J1853-4158's H I map because its single-pointing spectrum did not show an H I detection. We also included in Fig. 1 a deep GBT H I map of the 1H1613-097 field that was obtained under GBT programmes GBT20A-253 and GBT17B-015 (~1.2° in width). These maps were created by visually inspecting the spectrum extracted from the data cube integrated over one beam around the sight line (using the H I single-pointing detections as a guide). We then integrated channels with potential H I emission from the cloud of interest (velocities of 65 to 131 km s⁻¹ for [1919-2958, -123 to -56 km s⁻¹ for [1938-4326 and -201 to -150 km s⁻¹ for 1H1613-097]).

Beam-smearing analysis. We used the new FB HVCs' GBT H I maps to investigate small-scale H I structure by quantifying the effect of beam-smearing on our measurements. As we also had 1H1613-097's GBT map, we included it in our beam-smearing analysis. To quantify the beam-smearing effects, we extracted spectra from the GBT maps within four equally spaced beam-sized pointings, each centred on one half beamwidth away from the central quasar sight line, and one pointing centred on the sight line itself. We performed a boxcar smoothing of each spectrum by three channels and fitted Gaussians to each FB HVC. We then calculated each cloud's log \(N_{\text{H I}}\) in each pointing and took the largest difference between log \(N_{\text{H I}}\) from the central pointing and the four surrounding pointings as a beam-smearing error, \(e_{\text{beam}}\). We compiled the beam-smearing errors and standard deviation of both the H I velocity centroids and FWHM of fits in Supplementary Table 1. The beam-smearing errors were added to the H I column density errors in quadrature when calculating the metallicity of each cloud. We note that due to the stray radiation problems discussed above in the ‘Observations and data reduction’ section, J1919-2958's beam-smearing error could be affected by stray radiation. However, the resulting \(e_{\text{beam}}\) of 0.10 dex is a comparable to other beam-smearing error estimates on these angular scales in the literature.

The other sight line emissions either did not have H I emission maps available (LS 4825, 15109-0702 and PG 1522+101) or had their H I columns measured using Lyman lines from FUSE data with an infinitesimal beam size (MS-2NZG1 and PKS 2005-489). For LS 4825's H I measurements, we added in quadrature an assumed beam-smearing error of 0.15 dex to H I columns in metallicity calculations, a reasonable assumption for GBT and HST UV derived metallicities.

UV ion and H I column densities of the literature sample. For each cloud in the literature sample we used their respective UV ion and H I column densities given in each reference, with the exception of LS 4825-1/2, J1509-0702 and PG 1522+101. We have listed the UV and H I fit parameters used for metallicity measurements for the literature sample in Extended Data Fig. 4.

LS 4825-1 has overlapping narrow and wide O I components reported in the literature at 90.9 and 93.3 km s⁻¹ (ref. 39). To obtain an upper limit for LS 4825-1, we added the columns of both components and used the average \(v_{\text{IC}}\) and larger \(v_{\text{IC}}\) of the two throughout the paper. We also used VPFIT to recalculate the O I columns for two sources with apparent optical depth measurements in the literature from strongly blended absorption, J1109-0702 and PG 1522+101. For all other literature sources, we used the reported UV ion column densities. For MS-2NZG1 and 1H1613-097, we also used the literature reported H I column densities.

For the FB HVCs with H I limits, we calculated the H I column upper limit from GBT (1H1613-097; LS 4825-3/4), LAB' (J1509-0702) or Green Bank 140' (PG 1522+101) spectra. The H I column upper limit was calculated in two ways: using equation (2) with the mean root square and using equation (3) with three times the H I emission integrated over the velocity range of the respective O I absorption's FWHM. The higher column density from both of these methods was used as a conservative H I upper limit.

LS 4825's H I spectra had strongly blended multi-component positive and negative velocity emission, making it difficult to fit a unique set of Gaussians to the spectrum. The negative-velocity H I component between −110 and −40 km s⁻¹ was also reported to have one strong emission peak centred at −70.3 km s⁻¹ and one weak emission peak centred at −88.6 km s⁻¹. However, MgI and CII, both of which trace cool gas, have absorption components of nearly equal magnitude at similar negative velocities (see Extended Data Fig. 5). As LS 4825's spectrum was so complex, we decided to re-measure the H I emission for the FB HVCs.

For LS 4825's negative-velocity FB HVC component, we estimated the low-velocity Milky Way H I component's contribution to the high-velocity components by using HD 167402's H I spectrum as a 'foreground' emission model. We used the decomposed HD 167402's full H I spectrum into Gaussians with minimum residual widths. Then, using these Gaussians as a model, we removed HD 167402's negative-velocity emission peaks that were not likely to be associated with the low-velocity Milky Way H I component (velocities of −51.5 and −73.9 km s⁻¹, FWHM of 18.8 and 45.9 km s⁻¹ and peak amplitudes of 0.17 and 0.10 K, respectively; see Extended Data Fig. 5). HD 167402's residual low-velocity Milky Way H I emission had a slope that matched that of LS 4825 at negative velocities with only small variations, indicating that HD 167402's residual emission was a suitable model for LS 4825's low-velocity H I emission at negative velocities. We subtracted HD 167402's residual H I spectrum from LS 4825's and fitted LS 4825's remaining negative-velocity H I components with Gaussians using the UV absorption components as a guide and the minimum number of components needed to obtain a low-residual fit. The fit was accomplished with two Gaussians of nearly equal strength, matching the MgI and CII absorption trends (see Extended Data Fig. 5). We assumed that the −85.8 ± 1.7 km s⁻¹ H I component was associated with the −78.1 ± 1.9 km s⁻¹ SiII absorption because of their adjacent velocities.

UV ion and H I column densities of the literature sample. The positive velocity Milky Way emission for HD 167402 and LS 4825 were significantly different; this method therefore only works for negative-velocity clouds. For the positive velocity H I component within the OI absorption's FWHM of 19.8 km s⁻¹ and velocity centroid of 92.1 ± 0.8 km s⁻¹.

Metallicity measurements. We calculated the metalicities from the ion abundances \([X/H]\) as:

\[
[X/H] = \left[ \frac{X}{\text{H}} \right] + IC(X),
\]

where \(X/\text{H}\) is the solar abundance of that element (\(\odot\)) and \(IC(X)\) is the ionization correction, \(N_{\text{H}}\) and \(N_{\text{X}}\) are the atomic and hydrogen column densities, respectively, and \(\log(X/\text{H})\) is the solar abundance of that element (\(\odot\)). The ionization corrections are important for FB HVCs given their location close to the Galactic Centre and within the cone of a potential past Seyfert flare exposions to intense radiation fields. Furthermore, their low \([N/\text{H}1]\) values are indicative of high levels of ionization.

We derived the ionization corrections for the new FB HVCs by performing a suite of photoionization models using CLOUDY v17.0.2. The CLOUDY models were calculated for both an equilibrium case and a time-dependent case to explore the effects of a potential Seyfert flare on the ionization corrections. As J1919-2958 has two H I column densities, we ran two sets of CLOUDY models for this cloud; these models are compared in Supplementary Section 4. To increase our sample for the time-dependent models, we also included the FB HVC towards 1H1613-097. We discuss the ionization corrections for the rest of the sample below.

Equilibrium models. We first modelled the time-independent ICs for an ionization equilibrium state in CLOUDY. Physically, these models describe the steady state ionization conditions of clouds existing in the halo before a Seyfert flare event. These models were used as input parameters for the time-dependent models and were later used to confirm whether the time-dependent models strongly affected the present-day ionization corrections.
We adopted a plane-parallel geometry with a slab of uniform density illuminated on both sides by a position-dependent combined Galactic and extragalactic radiation field\textsuperscript{29-31}. The field had a normalization scaled to a distance of 10 kpc along the northern Fermi bubble line of sight to 151613-097. This field was also suitable for J1919-2958 and J1938-4326 given that the radiation field models are comparatively symmetric up to 10 kpc (ref. \textsuperscript{32}) as well as the similar absolute latitude of 1H1613-097 (b = 28.46\degree) with J1919-2958 (b = -18.77\degree) and J1938-4326 (b = -26.41\degree). We also included the cosmic ray background in our radiation field\textsuperscript{32}.

For each FB HVC, we constructed a grid of CLOUDY models over a range of hydrogen number densities (log $n_H$) between ~2 and 1 in 0.5 dex intervals, with the metallicity fixed to the ion abundance values presented in Extended Data Fig. 1. The model for each cloud was run until their respective measured H I column densities were reached. The value of log $n_H$ was determined by comparing the observed column density ratio [Si iii]/[Si ii] at each step in the grid of hydrogen densities, and interpolating to find the best match (see Supplementary Fig. 2 for the observed Si ii and Si iii absorption profiles). Si ii absorption associated with J1938-4326's FB HVC was not detected. We instead used the Si ii/Si iii ratio assuming that both ions have the same abundance relative to solar. Once a value for log $n_H$ was determined for each FB HVC, the model was run again for that specific value to obtain exact model results.

Non-equilibrium time-dependent models. There is strong evidence that an ~3.5-Myr-old Seyfert flare from the Galactic Centre impacted the Magellanic Stream and resulted in enhanced present-day H\textsuperscript{I} emission and UV ionization levels in the stream\textsuperscript{29}. As the FB HVCs are approximately ten times closer to the Galactic Centre than the Magellanic Stream, there may also be the contribution of ionization effects from the Seyfert flare on the FB HVCs. We used CLOUDY to follow the evolution of the FB HVCs near a time-variable incident radiation field. In this time-dependent non-equilibrium model, ionization and recombinations were not in balance and a net rate of change for an ion density occurred\textsuperscript{31,33}. The shape of the flare was modelled using the AGN spectrum built into CLOUDY, which consists of a multi-temperature plasma characterized by a rising power law with a high energy exponential cutoff and a "big blue bump" component peaking at ~1 Ryd. The intensity of the flare was specified by a rising power law with a high energy exponential cutoff and a 'big blue bump' which translated to 10$^9.25$ illuminating on both sides by a position-dependent combined Galactic and extragalactic radiation field\textsuperscript{59}.

Table 1 shows that the model results for the non-equilibrium models are comparable to the equilibrium models. This is not surprising since we used the same grid of models described above. In addition, we have not included models for the FB HVCs around J1509-0702, where the AGN spectrum was not available via the NRAO archive after the proprietary period ends on 9 July 2022.

The metallicity calculations (see Extended Data Fig. 1) we used for the non-equilibrium models were calculated for the beginning of the Seyfert flare event (t = 0 Myr) to estimate the ionization corrections for FB HVCs with O I detections and H II regions. For this sample we used the IC values calculated from log U = -3.0 and the other two IC values (log U = -3.5 and -2.5) served as the errors on the IC.

The Seyfert flare model was used to calculate the ionization corrections for FB HVCs with O I detections and H II regions. For this sample we used the IC values calculated from log U = -3.5 for the H II column limit as it provided an IC (O I) lower limit to our lower-limit metallicity calculations.

We did not calculate an IC for PKS 2053-489. PKS 2053-489’s metallicity estimate, drawn from the literature, was made by comparing the FB HVC’s FUSE and STIS absorption line ratios (Si iii, Si ii, O I and H Lyman series) to those of highly ionized Milky Way halo clouds with similar absorption columns and existing CLOUDY models\textsuperscript{34,35}. The IC for M5-ZNG1 was calculated with the CLOUDY equilibrium modelling described above. We chose an equilibrium model because the Seyfert flare event 3.5 Myr ago was shown not to have a lasting effect on the present-day ICs in other FB HVCs. Therefore, a full time-dependent treatment was deemed unnecessary. The equilibrium IC is shown in Extended Data Fig. 1.

Data availability
The HST/CO31MOS data for all sources used in this paper are available in MAST at https://doi.org/10.17909/zxzh-4x54 (ref. \textsuperscript{66}), including HST Program IDs 1533, 738, 825–842 (2010). The shape of the flare was modelled using the AGN spectrum built into CLOUDY, which consists of a multi-temperature plasma characterized by a rising power law with a high energy exponential cutoff and a "big blue bump" component peaking at ~1 Ryd. The intensity of the flare was specified by a rising power law with a high energy exponential cutoff and a 'big blue bump' which translated to 10$^9.25$ illuminating on both sides by a position-dependent combined Galactic and extragalactic radiation field\textsuperscript{59}.

The results are shown in Extended Data Fig. 1.

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Additional information

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Extended Data Fig. 1 | Full Metallicity Measurements. \(X_i\) represents the UV-detected ion used for metallicity calculations and \(v_{\text{UV}}\) is the FB HVCs' LSR velocity centroid for that ion. The ion absorption and \(\text{H}\)\(_i\) emission, \(\log N_{X_i}\) and \(N_{\text{H}i}\), respectively, are listed with the \(\text{H}\)\(_i\) column errors including beam smearing added in quadrature when available. We also list the ion abundances, \([X/\text{H}]\). The ionization correction, IC, calculations are discussed throughout the Methods section. \([X/\text{H}]\) is the corrected gas-phase elemental abundance and does not account for dust depletion. We include an \(\text{O}\)\(_i\) solar abundance for M5-ZNG1’s elemental abundance measurement that is updated from that in the literature\(^{33,54}\). For a discussion of the multiple \(\text{H}\)\(_i\) measurements for J1919-2958, see the Methods Section. For a discussion of dust depletion and the multiple \(\text{H}\)\(_i\) measurements for J1938-4326, see Supplementary Information Section 1.

| Reference | Sight Line | \(v_{\text{UV}}\) (km s\(^{-1}\)) | \(X_i\) | \(\log N_{X_i}\) (N in cm\(^{-2}\)) | \(\log N_{\text{H}i}\) (N in cm\(^{-2}\)) | \([X/\text{H}]\) | IC | \([X/\text{H}]\) |
|-----------|------------|----------------|--------|----------------|----------------|--------------|----|--------------|
| UV and \(\text{H}\)\(_i\) detections |
| TW | J1919-2958 | 97.8 ± 7.7 | \(\text{O}\)\(_i\) | 14.53 ± 0.04 | 18.30 ± 0.12 | −0.46 ± 0.14 | ≤ 17.62 | \(\geq -0.059\) ± 0.001 | \(\geq -0.52\) ± 0.14 |
| TW | J1938-4326 | −107.1 ± 8.2 | \(\text{C}\)\(_{\Pi}\) | 13.30 ± 0.07 | 18.61 ± 0.38 | −1.74 ± 0.39 | \(\geq -0.820\) ± 0.010 | \(\geq -2.56\) ± 0.39 |
| 17 | 1H1613-097 | −163 ± 1 | \(\text{O}\)\(_i\) | 14.28 ± 0.03 | 18.23 ± 0.21 | −0.64 ± 0.22 | \(\geq -0.820\) ± 0.010 | \(\geq -1.57\) ± 0.39 |
| 18 | LS 4825-1 | 92.1 ± 0.8 | \(\text{O}\)\(_i\) | ≥ 14.39 | 18.36 ± 0.15 | ≥ −0.66 | \(\geq -0.01\) ± 0.01 | \(\geq -0.67\) ± 0.39 |
| 18 | LS 4825-2 | −78 ± 1 | \(\text{S}\)\(_{\Pi}\) | 14.57 ± 0.05 | 19.14 ± 0.16 | 0.31 ± 0.17 | \(\geq -0.38\) ± 0.09 | \(\geq -0.07\) ± 0.39 |
| 49 | M5-ZNG1 | −124 ± 7 | \(\text{O}\)\(_i\) | 13.38 ± 0.08 | 16.50 ± 0.06 | 0.19 ± 0.11 | 0.31 | 0.50 ± 0.11 |
| 33 | PKS 2005-489 | 168 ± 10 | ... | ... | ... | ... | ... | < −0.70 |
| UV detections and \(\text{H}\)\(_i\) limits |
| TW | J1853-4158 | −120.2 ± 8.4 | \(\text{O}\)\(_i\) | 13.70 ± 0.12 | ≤ 17.20 | ≥ −0.19 | −0.04 | ≥ −0.23 |
| 17 | J1509-0702 | −115.2 ± 7.8 | \(\text{O}\)\(_i\) | ≥ 14.61 | ≤ 18.10 | ≥ −0.18 | −0.05 | ≥ −0.23 |
| 18 | LS 4825-3 | −205 ± 2 | \(\text{O}\)\(_i\) | 13.86 ± 0.05 | ≤ 17.52 | ≥ −0.35 | −0.01 | ≥ −0.36 |
| 18 | LS 4825-4 | −155 ± 1 | \(\text{O}\)\(_i\) | ≥ 14.86 | ≤ 17.75 | ≥ 0.42 | −0.01 | ≥ 0.41 |
| 17 | PG 1522+101 | −99.8 ± 8.3 | \(\text{O}\)\(_i\) | 14.14 ± 0.10 | ≤ 17.92 | ≥ −0.47 | −0.06 | ≥ −0.53 |
Extended Data Fig. 2 | UV and H\textsc{i} Fit Parameters for New Sight Lines. The second column represents the allowed velocity range of gas co-rotating with the Milky Way disk in each quasar’s direction\textsuperscript{67}. \textit{X} represents the ion used for metallicity calculations. The UV Voigt fit parameters of \textit{X} for each cloud are the LSR velocity centroid, \( v_{0\text{UV}} \), the Doppler broadening parameter (b-value), and the log column density, \( \log N_{X} \). The UV velocity centroid errors include the 7.5 km s\textsuperscript{−1} COS zero-point uncertainty. The H\textsc{i} Gaussian fit parameters are the LSR velocity centroid, \( v_{0\text{HI}} \) and full-width-half-max, FWHM. For a Gaussian profile, the relation between FWHM and b-value is FWHM = 1.665\( b \). The H\textsc{i} log column density, \( \log N_{\text{HI}} \), is given in the last column.

J1853-4158’s H\textsc{i} column was obtained using the spectrum’s rms, as described in the Methods Section. J1919-2958’s H\textsc{i} column was obtained by through the “flip-and-subtract” method (described in the Methods Section) using two velocity ranges for integration, which encompass all potential emission associated with the FB HVC (upper column limit) and emission least affected by stray radiation (lower column limit). J1938-4326’s H\textsc{i} column was obtained using a Gaussian fit to emission. Second and third measurements of the H\textsc{i} column were made by integrating over the C\textsc{ii} absorber’s FWHM and then using Equation (2); see Supplementary Information Section 1 for more details.

| Sight line       | Allowed Velocities (km s\textsuperscript{−1}) | X' | UV Voigt Fit Parameters | H\textsc{i} Integration | H\textsc{i} Gaussian Fit | \( \log N_{\text{HI}} \) (N in cm\textsuperscript{−2}) |
|------------------|-----------------------------------------------|----|------------------------|--------------------------|---------------------------|--------------------------------------------------|
| J1853-4158      | −49 : 0                                       | O I| −120.2 ± 8.4           | 16.7 ± 5.2               | 13.70 ± 0.12              | ...                                           |
| J1919-2958      | 0 : 63                                        | O I| 97.8 ± 7.7             | 25.9 ± 2.5               | 14.53 ± 0.04              | 82.7, 133.4                                    |
| J1938-4326      | −13 : 0                                       | C II| −107.1 ± 8.2           | 24.0 ± 4.7               | 13.30 ± 0.07              | −127.4, −87.3                                 |

For a Gaussian profile, the relation between FWHM and b-value is FWHM = 1.665\( b \). The H\textsc{i} log column density, \( \log N_{\text{HI}} \), is given in the last column.
Extended Data Fig. 3 | Flipped-and-subtracted GBT H\textsc{i} spectrum for J1919-2958 and 1938-4326. The blue shaded spectrum represents the original H\textsc{i} spectrum at a resolution of 1 km s\textsuperscript{-1}. The maximum velocity range used to calculate the H\textsc{i} column densities is shaded in grey. The black line is the flipped-and-subtracted spectra smoothed to 2 km s\textsuperscript{-1} in the integrated velocity ranges including an additional 7 channels on each side of those velocity ranges. 1938-4326’s flipped-and-subtracted spectrum is used as a check on the Gaussian H\textsc{i} column listed in Extended Data Fig. 2 and is discussed in Supplementary Information Section 2.
### Extended Data Fig. 4 | UV and HⅠFit Parameters for Literature Sight Lines

This table lists UV and HⅠfit parameters for the literature FB HVCs, similar to that done for the new sight lines in Extended Data Fig. 2. M5-ZNG1 has a literature HⅠmeasurement based on a combination of FUSE profile fitting and curve-of-growth measurements\(^{34}\). J1509-0702 and PG 1522+10 have HⅠmeasurements based on their average rms of emission-free channels (rms of 0.055 and 0.032 K, respectively). PKS 2005-489’s log \( N_{\text{HI}} \) is from Lyman series measurements in the literature\(^{33} \).

| Sight line   | \( X^2 \) | UV Voigt Fit Parameters | HⅠIntegration | HⅠ Gaussian Fit | \( \log N_{\text{HI}} \) |
|--------------|----------|-------------------------|----------------|----------------|-------------------------|
|              |          | \( V_0\) (km s\(^{-1}\)) | b-value (km s\(^{-1}\)) | \( \log N_{\text{HI}} \) (N in cm\(^{-2}\)) | \( \log V_{\text{min}} \) (km s\(^{-1}\)) | \( \log V_{\text{min}} \) (km s\(^{-1}\)) | \( V_{0\text{-HI}} \) (km s\(^{-1}\)) | FWHM (km s\(^{-1}\)) | (N in cm\(^{-2}\)) |
| 1H1613-097   | O I      | –163 ± 1                | 17.6 ± 1.7    | 14.28 ± 0.03 | ... | ... | 172.2 ± 0.1 | 12.8 ± 0.8 | 18.23 ± 0.03 |
| LS 4825-1    | O I      | 92.1 ± 0.8              | 11.9 ± 2.5    | >14.39      | 82.0 | 101.9 | ... | ... | 18.36 ± 0.01 |
| LS 4825-2    | S II     | –78 ± 1                 | 6.9 ± 0.6     | 14.57 ± 0.05 | ... | ... | –85.8 ± 1.7  | 26.8 ± 2.0 | 19.14 ± 0.05 |
| LS 4825-3    | O I      | –205 ± 2                | 18.6 ± 2.5    | 13.86 ± 0.05 | –221.1 | –190.3 | ... | ... | ≤17.52 |
| LS 4825-4    | O I      | –155 ± 1                | 14.2 ± 0.5    | >14.86      | –167.4 | –143.2 | ... | ... | ≤17.75 |
| M5-ZNG1      | O I      | –124 ± 7                | ...           | 13.38 ± 0.08 | ... | ... | ... | ... | 16.50 ± 0.06 |
| J1509-0702   | O I      | –115.2 ± 7.8            | 9.6 ± 5.1     | >14.61      | ... | ... | ... | ... | ≤18.10 |
| PG 1522+101  | O I      | –99.8 ± 8.3             | 12.7 ± 6.3    | 14.14 ± 0.10 | ... | ... | ... | ... | ≤17.92 |
| PKS 2005-489 | ...      | 168 ± 10                | ...           | ...         | ... | ... | ... | ... | 16.66 ± 0.83 |
Extended Data Fig. 5 | Deconvolution of LS 4825’s H\textsubscript{i} spectrum. Left: LS 4825’s and HD 167402’s H\textsubscript{i} spectra plotted against HD 167402’s low-velocity Milky Way component and LS 4825’s residual H\textsubscript{i} spectrum after subtracting HD 167402’s low-velocity Milky Way component. We also plot LS4825’s O\textsubscript{i} \( \lambda 1302 \) and C\textsubscript{i} \( \lambda 1560 \) spectrum for comparison. Right: The individual and combined Gaussian fits to LS 4825’s residual negative-velocity components.
Extended Data Fig. 6 | CLOUDY Model Results. $X^i$ represents the ion used for the metallicity calculations and $v_{v0\text{UV}}$ is the UV velocity centroid of each component. The logarithmic $\text{Si}\text{iii}$/ $\text{Si}\text{ii}$ ion ratio, $[\text{Si}\text{iii}/\text{Si}\text{ii}]$, is calculated using the column densities measured in previous Fermi Bubble UV Surveys\textsuperscript{17,20}; for J1938-4326 we use the $[\text{Si}\text{iii}/\text{C}\text{ii}]$ ratio. $U$ is the ionization parameter, equal to the ratio of the ionizing photon density to the gas density. The log hydrogen number density and column density of the clouds are given as $\log n_H$ and $\log N_H$, respectively. The depth is the calculated size of the cloud along the line-of-sight. The present-day ionization corrections are given as $IC(X^i)$ Eq. for the equilibrium models, and $IC(X^i) \Phi(H)_8$ and $IC(X^i) \Phi(H)_10$ for the time-dependent models at two ionizing photon fluxes, $\log \Phi(H)=8$ and 10, respectively.

| Sight line | $X^i$ | $v_{v0\text{UV}}$ (km s$^{-1}$) | $[\text{Si}\text{iii}/\text{Si}\text{ii}]$ | $\log U$ Eq. | $\log n_H$ (n cm$^{-3}$) | $\log N_H$ (N cm$^{-2}$) | Depth (pc) | $IC(X^i)$ Eq. | $\Phi(H)_8$ | $\Phi(H)_10$ |
|-----------|------|-------------------------------|-------------------------------|-------------|----------------|----------------|-------------|---------------|-------------|-------------|
| J1919-2958 | O I  | 97.8 ± 7.7                   | $\geq -0.37$                  | $\leq -0.57$ | 19.52       | 19.66         | $\geq 41$   | $\geq -0.062$ | $\geq -0.060$ | $\geq -0.059$ |
| 1H1613-097 | O I  | $-163 \pm 1$                 | $\geq -0.45$                  | $\leq -0.35$ | 19.34       | 19.66         | $\geq 16$   | $\geq -0.067$ | $\geq -0.066$ | $\geq -0.065$ |
| J1938-4326 | C II | $-107.1 \pm 8.2$             | $-0.67$                       | $-3.11$      | $-0.94$     | 20.02         | 298         | $-1.08$       | $-0.830$     | $-0.820$     |
Extended Data Fig. 7 | Time-dependent ionization corrections versus time calculated from CLOUDY models. The results are given for two ionizing fluxes: \( \log \Phi(H) = 8 \) (solid line) and 10 (dashed line), where \( \Phi(H) \) has units of photons cm\(^{-2}\) s\(^{-1}\) and where colored shading shows intermediate ionizing fluxes. Each panel shows the ionization correction across the full time interval modeled (0-3.6 Myr), with an inset plot magnifying the flatter part of the curves after the initial flash to emphasize the late-time behavior. The equilibrium results are marked with an ‘x’ at 3.6 Myr in each panel.