Cold gas in the Milky Way’s nuclear wind

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The centre of the Milky Way hosts several high-energy processes that have strongly affected the inner regions of our Galaxy. Activity from the super-massive black hole at the Galactic Centre, which is coincident with the radio source Sagittarius A*, and stellar feedback from the inner molecular ring1 expel matter and energy from the disk in the form of a galactic wind2. Multiphase gas has been observed within this outflow, including hot highly ionized3-4 (temperatures of about 10^6 kelvin), warm ionized5-6 (10^4 to 10^5 kelvin) and cool atomic7-8 (10^3 to 10^4 kelvin) gas. However, so far there has been no evidence of the cold dense molecular phase (10 to 100 kelvin). Here we report observations of molecular gas outflowing from the centre of our Galaxy. This cold material is associated with atomic hydrogen clouds travelling in the nuclear wind8. The morphology and the kinematics of the molecular gas, resolved on a scale of about one parsec, indicate that these clouds are mixing with the warmer medium and are possibly being disrupted. The data also suggest that the mass of the molecular gas outflow is not negligible and could affect the rate of star formation in the central regions of the Galaxy. The presence of this cold, dense and high-velocity gas is puzzling, because neither Sagittarius A* at its current level of activity nor star formation in the inner Galaxy seems to be a viable source for this material.

At a distance of only 8.2 kpc from the Sun (ref. 9), the Galactic Centre provides a unique laboratory for studying the complex physical processes that occur within a galactic outflow. The Fermi bubbles2,10, two giant lobes extending up to -10 kpc from the Galactic plane, are thought to outline the current boundaries of the Milky Way’s nuclear wind. Several hundred neutral gas clouds have been found recently within this volume through observations of the atomic hydrogen (H I) line at a wavelength of λ = 21 cm (refs. 7,8). Figure 1 shows a column density map of H I clouds in the nuclear wind8 detected with the Green Bank Telescope (GBT). Although the bulk of the cloud population lies within the boundaries of the Fermi bubbles (green dashed line11), it has not been established whether this outflowing H I gas arises from the same event that generated the Fermi bubbles. These clouds were identified through their anomalous line-of-sight velocities, which are incompatible with Galactic rotation and can instead be described using a biconical wind model in which clouds accelerate from the Galactic Centre, reaching a maximum velocity of 330 km s^{-1} after about 2.5 kpc (refs. 8,12). To assess whether outflowing H I structures carry molecular gas, we targeted two objects (hereafter, MW-C1 and MW-C2), highlighted by red boxes in Fig. 1, in the 12CO(2 → 1) emission line at 230.538 GHz with the 12-m Atacama Pathfinder Experiment (APEX) telescope. These two clouds have relatively high H I column densities (>10^{19} cm^{-2}) and show an elongated head-to-tail morphology along the direction pointing away from the Galactic Centre. We mapped both clouds in 12CO(2 → 1) emission over a 15′ × 15′ field centred on the peak of the H I emission, at a spatial resolution of 28″ (full-width at half-maximum, FWHM), corresponding to ~1 pc at the distance of the Galactic Centre, and a spectral resolution of 0.25 km s^{-1}. These data revealed molecular gas outflowing from the centre of our Galaxy.

Fig. 1 | Atomic hydrogen gas outflowing from the Galactic Centre. The colour scale shows the column density of anomalous H I clouds in the Milky Way’s nuclear wind, detected with GBT8. The green dashed line is the boundary of a volume-filled model for the Fermi bubbles11. The two H I clouds observed in the 12CO(2 → 1) line with APEX are marked by red boxes.
Figure 2 shows H\textsubscript{i} column density maps (Fig. 2a, c) from GBT observations and integrated brightness temperature maps (Fig. 2b, d) from the 12CO(2 → 1) line obtained with APEX for MW-C1 and MW-C2. Higher-resolution H\textsubscript{i} data from the Australia Telescope Compact Array (ATCA) for MW-C2 are also overlaid as contours on the CO map. CO velocity fields and three representative spectra across each field are presented in Fig. 3. CO emission is detected in both H\textsubscript{i} clouds, with substantial morphological and kinematical differences between them. MW-C1 shows five distinct compact clumps of molecular gas concentrated towards the part of the H\textsubscript{i} cloud that faces the Galactic Centre (GC). At least three clumps have a velocity gradient along the direction pointing towards the tail of the H\textsubscript{i} cloud. All the CO emission in MW-C1 lies in the local-standard-of-rest (LSR) velocity range $V_{\text{LSR}} \approx 160$–$170$ km s$^{-1}$, with typical FWHM line widths of ~2–3 km s$^{-1}$ (see spectra in Fig. 3). By contrast, in MW-C2 most of the CO emission is spread over a larger velocity range than in MW-C1, spanning $300$ km s$^{-1}$, and the velocity field does not show any clear ordered motion. The observed features indicate that cold gas in MW-C2 is interacting and mixing with the surrounding medium more efficiently than in MW-C1, resulting in a more turbulent molecular gas. An interpretation of the differences in the morphokinematics of the molecular gas in the two clouds is that we are witnessing two evolutionary stages of a cold cloud being disrupted by interaction with a hot flow. Our idealized biconical wind model with a maximum wind velocity of $330$ km s$^{-1}$ places MW-C1 at a distance of $0.8$ kpc and MW-C2 at a distance of $1.8$ kpc from the Galactic Centre, implying that MW-C2 may have been within the nuclear outflow twice as long (7 Myr, versus 3 Myr for MW-C1). Our model also predicts that MW-C2 is moving faster than MW-C1 ($\approx 300$ km s$^{-1}$ versus $\approx 240$ km s$^{-1}$). The observed characteristics of the two clouds may also be explained in terms of different local conditions of the hot outflow. A larger and more complete sample of molecular gas detections in outflowing clouds is needed to provide a more robust picture.

The two clouds analysed in this work have atomic gas masses of $M_\text{a} = 220M_\odot$ (MW-C1) and $M_\text{a} = 800M_\odot$ (MW-C2), as derived from the GBT H\textsubscript{i} data ($M_\odot$, mass of the Sun). All mass measurements from...
observations are scaled by a factor of 1.36 to account for the presence of helium. It is not straightforward to estimate the mass of molecular matter, because the gas may have considerable opacity in the $^{12}$CO($2 \rightarrow 1$) line and the appropriate CO-to-H$_2$ conversion factor $X_{\text{CO}}$ in the Milky Way’s wind is unknown. We used the observed CO integrated brightness temperatures, cloud radii and line widths to constrain the acceptable $X_{\text{CO}}$ values by means of chemical and thermal modelling of a cloud undergoing dissociation by photons and cosmic rays. We found that $X_{\text{CO}}$ for the $^{12}$CO($2 \rightarrow 1$) transition in our clouds lies in the range (2–40) $\times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$. The lowest value, $X_{\text{CO}} = 2 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$, is consistent with the Galactic conversion factor$^{13}$, and was used to derive lower limits to the molecular gas mass $M_{\text{mol}}$. We obtained $M_{\text{mol}} \geq 380 M_\odot$ for MW-C1 and $M_{\text{mol}} \geq 375 M_\odot$ for MW-C2, implying molecular-to-total gas mass fractions of $f_{\text{mol}} = (M_{\text{mol}}/(M_{\text{mol}} + M_\text{HII})) \geq 0.64$ and $f_{\text{mol}} \geq 0.32$, respectively. We emphasize that these values are lower bounds and the molecular gas mass may be higher by a factor of ten.

As a consequence, the total mass of molecular gas in the nuclear wind of the Milky Way is large. Under the conservative assumption of an average $f_{\text{mol}} = 0.3–0.5$ for all outflowing H I clouds in the GBT sample, and using an atomic outflow rate of $M_\text{HII} = 0.1 M_\odot$ yr$^{-1}$, we estimated an outflow rate of $M_\text{HII} \geq (0.05–0.1) M_\odot$ yr$^{-1}$ in molecular gas. This value is of the same order of magnitude as the star formation rate (SFR) of the Central Molecular Zone$^{14}$ (CMZ), implying a molecular gas loading factor $\eta = M_{\text{mol}}$/SFR at least of the order of unity at a distance of 1 kpc from the Galactic plane, similar to that estimated in nearby starburst galaxies$^{15}$. This cold outflow affects the gas cycle in the inner Galaxy and may constitute an important mechanism that regulates the star formation activity in the CMZ.

From a theoretical point of view, such a large amount of high-velocity molecular gas is puzzling$^{23}$. It is believed that cool gas in a disk can be lifted and accelerated by both drag force from a hot outflow$^{24}$ and by radiation pressure$^{25}$. This requires a source of strong thermal feedback and/or radiation feedback. The Milky Way does not currently have an active galactic nucleus (AGN), nor is the SFR of the inner Galaxy comparable to that of starburst galaxies with known molecular winds (for example, NGC253)$^{15}$. Current simulations of AGN-driven winds have focused on very powerful AGNs$^{19,20}$ and there have been no investigations studying whether a relatively small black hole like Sagittarius A* could expel large amounts of cold gas, even if it had undergone a period of activity in the recent past. On the other hand, the current SFR of the CMZ is not large enough to explain the estimated outflow rate of cold gas$^{23}$, and no observational evidence so far suggests a sizable change in the SFR of the CMZ in the last few million years$^{22}$. A scenario in which the star formation in the CMZ is episodic on a longer cycle$^{23,24}$ (10–50 Myr) and is currently near a minimum might help to partly reconcile the observed and predicted cool gas mass loading rates, although our wind model suggests that the lifetimes of cold clouds are shorter than 10 Myr. Cosmic rays are also believed to contribute to the pressure on cold gas$^{25}$, but their role is only just starting to be understood and needs observational constraints. Moreover, in either an AGN- or a starburst-driven wind, the extent to which cold gas survives under acceleration is a matter of debate$^{23,26}$, and several different mechanisms have been investigated to extend the lifetime of cold gas in a hot wind (for example, magnetic fields$^{27}$ and thermal conduction$^{28}$). An alternative scenario has been recently proposed in which high-velocity cool neutral gas (temperature $T < 10^4$ K) forms directly within the outflow as a consequence of mixing between slow-moving cool clouds and the fast-moving hot wind$^{29-31}$. This mechanism overcomes the problem of accelerating dense material without disrupting it, and may explain the high velocities observed in cool outflows. However, current simulations cannot trace the gas down to the molecular phase.

In conclusion, this detection of outflowing cold molecular gas in the Milky Way is a challenge for current theories of galactic winds in regular star-forming galaxies, because none of the above processes...
seems able to easily explain the presence of fast molecular gas in the Milky Way’s wind. Targeted observations of molecular gas tracers in the Milky Way’s nuclear wind are expected to contribute considerably to our understanding of these fascinating phenomena.

**Online content**

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-020-2595-z.
Observations and data reduction

Observations of the $^{12}$CO(2 → 1) emission line at 230.538 GHz were made with the 12-m APEX antenna6 using the PI230 heterodyne receiver (ESO project 0104.B-0106A; principal investigator E.M.D.T.). The spectrometer covers a bandwidth of 8 GHz at a spectral resolution of 61 kHz, corresponding to a velocity resolution of about 0.04 km s$^{-1}$ at 230 GHz. The beam size at this frequency is 27.8 (FWHM), the main-beam efficiency is 0.72 and the jansky-to-kelvin conversion factor is 35. We observed our targets in on-the-fly position-switching mode, integrating for 1 s every 9°. Both fields were 15 × 15 wide, centred at (RA, dec.)$_{J2000}$ = (17 h 56 min 34.0 s, −32°29′14″) for MW-C1 and at (RA, dec.)$_{J2000}$ = (17 h 18 m 22.2 s, −27°56′28″) for MW-C2. The observed regions are shown in red boxes in Figs. 1, 2. The total integration time was approximately 25 h for each field. Throughout the observing session (September to November 2019), the precipitable water vapour varied between 0.6 mm and 3 mm.

We reduced the data using the Continuum and Line Analysis Software (CLASS) from the GILDAS package. A first-order baseline was subtracted from the calibrated spectra by interpolating the channels outside the velocity windows in which we expected to see the emission based on the H I observations. The spectra were then smoothed in velocity and mapped onto a grid with a pixel size of 9″ and a channel width of 0.25 km s$^{-1}$. The root-mean-square noise ($\sigma_{\text{rms}}$) in the final data cubes was 63 mK and 55 mK for MW-C1 and MW-C2, respectively, in a 0.25 km s$^{-1}$ channel.

Atomic gas and molecular mass

The H I GBT data and the $^{12}$CO(2 → 1) APEX data were analysed to estimate the atomic and molecular gas masses, respectively. First, the three-dimensional source finder DUCHAMP$^{34}$ was applied to the data cubes to identify regions of sizable emission. During this process, we set a primary threshold to identify emission peaks at $5\sigma_{\text{rms}}$ and reconstructed sources by adding pixels down to a secondary threshold of $2.5\sigma_{\text{rms}}$.

The column density at a given position (x, y) on the sky can be written as:

$$N_d(x, y) = C \int T_b(x, y, \nu) d\nu,$$

where the integral considers pixels in only one detection, $T_b$ is the line brightness temperature, $d\nu$ is the channel width (1 km s$^{-1}$ for GBT and 0.25 km s$^{-1}$ for APEX) and $C$ is a constant. For the H I line, under the assumption that the gas is optically thin, the constant is $2.8 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$. For CO lines, this constant is also known as the CO-to-H$_2$ conversion factor $X_{\text{CO}}$ (ref. 13). Because the conversion factor varies by an order of magnitude, ranging between $2 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ and $4 \times 10^{21}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$, depending on the combination of radiation field and cosmic-ray ionization rate, the value of $X_{\text{CO}}$ is varied by an order of magnitude between $2 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (that is commonly assumed in the Milky Way disk$^{38}$) and $10^{21}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (that is commonly assumed in the Galaxy disk). We used $X_{\text{CO}}$ in this study to represent the gas column density and to constrain the CO-to-H$_2$ conversion factor of the clouds.

The total mass of gas can be calculated as:

$$M = 1.36 m D^2 \int N_d(x, y) dx dy,$$

where the factor 1.36 takes into account helium, $D = 8.2$ kpc is the adopted distance to the clouds, $m$ is the mass of atomic/molecular hydrogen for atomic/molecular gas, $dx$ and $dy$ are the pixel sizes in radians (105′′ for GBT, 9″ for APEX). The observed properties and estimated masses are summarized in the Extended Data Table 1.

Radiative-transfer models

We used the chemistry and radiative-transfer code DESPOTIC$^{37}$ to constrain the CO-to-H$_2$ conversion factor of the clouds. DESPOTIC computes the chemical and thermal state of an optically thick cloud given its volume density and column density. The turbulent velocity dispersion of the gas was assumed to be 1–5 km s$^{-1}$ (see Fig. 3) in our modelling. The chemical equilibrium calculation uses solar abundances for dust and all elements in the H–C–O chemical network$^{26}$, whereas the thermal equilibrium calculation includes heating by cosmic rays, the grain photoelectric effect, cooling by the H I, C I, C II, O I and CO lines, and collisional energy exchange between dust and gas. Level populations were calculated using an escape probability method, with escape probabilities estimated using the spherical geometry option of DESPOTIC.

We investigated different combinations of the interstellar radiation field $\chi$ and the cosmic-ray ionization rate $\zeta$ through a set of DESPOTIC models using log($\chi$/$G_0$) = −1, 0, 1, 2, where $G_0$ is the solar radiation field$^{49}$ and log($\zeta(s^{-1})$) = [−16, −15, −14]. The interstellar radiation field was varied between subsolar ($\chi = 0.1 G_0$) and highly supersolar ($\chi = 100 G_0$) values, representing a highly star-forming environment like the CMZ. The cosmic-ray ionization rate ranges from the value measured in the solar neighbourhood$^{30}$ ($\zeta = 10^{-16} s^{-1}$) to the estimated upper limit for the CMZ$^{31}$ ($\zeta = 10^{-14} s^{-1}$). We stress that our CO clouds lie at about 1 kpc from the Galactic plane and that both the interstellar radiation field and the cosmic-ray ionization rate are expected to drop with distance from the disk. Therefore, although the estimated values of $\chi$ and $\zeta$ in the CMZ are orders of magnitude higher than in the solar neighbourhood, models with intermediate interstellar radiation fields and cosmic-ray ionization rates should be more representative of the conditions high in the Milky Way’s wind.

For each model, DESPOTIC returned the $^{12}$CO(2 → 1) integrated brightness temperature ($T_{\text{co}}$) as a function of the number density ($n_{\text{H}_2}$) and column density ($N_{\text{H}_2}$) of molecular hydrogen. We only considered solutions consistent with the observed integrated brightness temperature (1–5 K km s$^{-1}$; see Fig. 2) and observed cloud radius of $R = 0.75 n_{\text{H}_2}/N_{\text{H}_2} \sim 1$–5 pc. We calculated the expected CO-to-H$_2$ conversion factor $X_{\text{CO}} = n_{\text{H}_2}/T_{\text{co}}$ for the $^{12}$CO(2 → 1) transition. We found that there are no acceptable solutions for a strong interstellar radiation field ($\log(\chi/G_0) \geq 1$), which indicates that molecular clouds with the observed properties cannot exist in the presence of a CMZ-like radiation field. Instead, models with solar and subsolar radiation fields returned solutions compatible with the observational constraints for any cosmic-ray ionization field. An interstellar radiation field weaker than the one produced in the CMZ is therefore more representative of the environment at 1 kpc above the Galactic Centre. The predicted $X_{\text{CO}}$ varies by an order of magnitude, ranging between $2 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ and $4 \times 10^{21}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$, depending on the combination of radiation field and cosmic-ray ionization rate. The value of $X_{\text{CO}}$ is $2 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ in the Milky Way disk$^{38}$ and used in this study is consistent with the smallest values returned by our radiative-transfer models, obtained with a weak, subsolar radiation field and a solar-like cosmic-ray ionization rate of $\zeta = 10^{-16} s^{-1}$. As a consequence, the molecular gas masses calculated in this work probably represent lower limits to the real cold gas mass in our CO clouds.

Wind kinematic model

To estimate the position, velocity and lifetime of MW-C1 and MW-C2, we used a biconical wind model$^{12}$ calibrated on the full population of H I clouds. This model is based on the assumption that clouds were launched from a small region close to the centre of the Galaxy and are moving with a purely radial velocity $V_r$, where $r$ is the distance from the Galactic Centre. For simplicity, we considered models of the form:

$$V_r(r) = \begin{cases} \frac{V_i + (V_{\text{max}} - V_i) r}{r_i} & \text{for } r < r_i, \\ V_{\text{max}} & \text{for } r \geq r_i, \end{cases}$$

where the factor 1.36 takes into account helium, $D = 8.2$ kpc is the adopted distance to the clouds, $m$ is the mass of atomic/molecular hydrogen for atomic/molecular gas, $dx$ and $dy$ are the pixel sizes in radians (105′′ for GBT, 9″ for APEX). The observed properties and estimated masses are summarized in the Extended Data Table 1.
where $V_i$ is the initial velocity at $r = 0$ and $r_i$ is the scale distance at which the maximum velocity $V_{\text{max}}$ is reached. Equation (3) describes a kinematic model in which clouds are subjected to a constant acceleration up to $r_i$ and maintain a constant velocity at distances $r \geq r_i$. Although equation (3) is purely empirical and chosen to reproduce the H\textsc{i} data, recent hydrodynamical simulations of starburst-driven winds have found qualitatively similar trends for the velocity of the cool gas with distance\(^9\). The LSR velocity $V_{\text{LSR}}$ of a cloud travelling in the wind and seen at Galactic coordinates $(l, b)$ can be written as:

$$V_{\text{LSR}}(l, b, r) = V_w(r)[\sin \phi \sin b - \cos \phi \cos \theta \cos(l + \theta)] - V_0 \sin \theta \sin b,$$

where the polar angle $\phi$ and the azimuthal angle $\theta$ can be easily written as a function of $(l, b, r)$ (ref.\(^9\)) and $V_0 = 240$ km s\(^{-1}\) is the rotation velocity of the LSR around the Galactic Centre\(^{36}\). In our model, clouds are restricted inside a bicone with half-opening angle $\phi_{\text{max}}$. We constrained the four free parameters of this model, $V_w$, $V_{\text{max}}$, $r_i$ and $\phi_{\text{max}}$, by matching the LSR velocity distributions predicted by our model with that observed from the H\textsc{i} cloud population\(^{13}\).

Our fiducial model is a biconical wind with opening angle $\phi_{\text{max}} = 70^\circ$, where clouds accelerate from an initial velocity of $V_i = 200$ km s\(^{-1}\) to a maximum velocity of $V_{\text{max}} = 330$ km s\(^{-1}\) at $r_i = 2.5$ kpc. According to this wind model, MW-C1 and MW-C2 have travelled a distance of 0.8 kpc and 1.8 kpc from the Galactic Centre in about 3 Myr and 7 Myr, and their current outflow velocity is about 240 km s\(^{-1}\) and 300 km s\(^{-1}\), respectively.

**Data availability**

The APEX raw datasets analysed for this study will be available at the end of the proprietary period (September 2020) on the ESO archive, http://archive.eso.org/eso/archive main.html. The GBT raw datasets are publicly available at the NRAO archive, https://science.nrao.edu/facilities/gbt/software-and-tools. Fully reduced data are available from the corresponding author on reasonable request.

**Code availability**

The software used in this work is publicly available. The GILDAS/CLASS packages for submillimetre data reduction can be found at https://www.iram.fr/IRAMFR/GILDAS. The DUCHAMP source finder can be downloaded from https://www.atnf.csiro.au/people/MatthewWhiting/Duchamp. The DESPOTIC radiative-transfer code is available at https://bitbucket.org/krumholz/despotic.
## Extended Data Table 1 | Properties of molecular gas clouds outflowing from the Galactic Centre

|     | $\ell$  | $b$    | $z$  | $r$  | $T_{b,\text{peak}}$ | FWHM  | Vel. range | $M_{\text{mol}}$ | $M_{\text{at}}$ |
|-----|--------|--------|------|------|---------------------|-------|------------|------------------|----------------|
| MW-C1 | 358.14 | -3.84  | 0.6  | 0.8  | 1.5                 | 2 - 3 | 160 - 170  | 380              | 220            |
| MW-C2 | 357.58 | 5.56   | 0.9  | 1.8  | 0.5                 | 5 - 12| 250 - 280  | 375              | 800            |

Shown are the Galactic coordinates ($\ell$, $b$), the height from the Galactic plane ($z$), the distance from the Galactic Centre ($r$) from our biconical outflow model\(^5\); the peak $^{12}\text{CO}(2 \rightarrow 1)$ brightness temperature ($T_{b,\text{peak}}$); typical CO line widths (FWHM); the velocity range of the CO line in the LSR; the lower limits to the molecular masses ($M_{\text{mol}}$), derived from $^{12}\text{CO}(2 \rightarrow 1)$ data; and atomic gas masses ($M_{\text{at}}$), derived from HI data. Masses include helium.