Gone with the breeze: A subsonic outflow solution to the Fermi bubbles problem

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ABSTRACT

The origin of the Fermi bubbles, which constitute two gamma-rays emitting lobes above and below the Galactic plane, remains unclear. The possibility that the Fermi bubble gamma-rays emission originates from hadronic cosmic-rays advected by a subsonic Galactic outflow is explored. Such a solution is called a Galactic breeze. This model is motivated by UV absorption line observations of cold clouds expanding from the Galactic center to high latitudes. For this purpose the hydrodynamical code PLUTO has been used in combination with a cosmic ray transport code. A model of the Galactic gravitational potential has been determined through constraints derived from the Gaia second data release. It is found that a Galactic breeze can be collimated by the surrounding gas and is indeed able to reproduce the observed Fermi-LAT energy flux at high Galactic latitudes. Following these results a prediction concerning the gamma-rays emission for 1-3 TeV photons is made for future comparison with CTA/SWGO measurements.

Key words: Galaxy: halo – gamma-rays: galaxies – cosmic rays – ISM: jets and outflows

1 INTRODUCTION

Observations and measurements have provided evidence of outflows in galactic centers (GCs) for several decades (Lynds & Sandage 1963; Burbidge et al. 1964; Mathews & Baker 1971; Songaila 1997). Such outflows have also been observed from the Milky-Way in a broad energy range from radio (Lockman 1984) to X-ray (Morris & Serabyn 1996; Cheng et al. 1997).

A decade ago, two Galactic bubbles extending above and below the GC were first detected with the Fermi-LAT instrument in the gamma-rays energy band (Su et al. 2010; Dobler et al. 2010). The extension of this emission is \( \sim 50^\circ \) in Galactic latitude and \( \sim 40^\circ \) in Galactic longitude. Furthermore, the spectral energy distribution of this gamma-rays emission is rather hard, exhibiting a spectral downturn or cutoff at an energy of \( \sim 300 \text{ GeV} \) (Ackermann et al. 2014). The brightness intensity of this emission appears approximately constant within the bubbles, with a sudden sharp edge feature observed at their boundary (Ackermann et al. 2014). These gamma-rays bubbles are potentially a counterpart of the microwave haze (Finkbeiner 2004; Planck Collaboration et al. 2013), with both exhibiting hard spectra. In the X-ray band, recent observations of larger scale eROSITA bubbles, which appear to ensnarl the Fermi bubbles, are likely connected to the Fermi bubble structures (Predehl et al. 2020).

Despite the wealth of observational data, there remains no clear consensus about the underlying mechanism that produces the outflows responsible for the formation of these bubbles. Three features must be fully explained to give a satisfying theory (Yang et al. 2018). These are related to the emission mechanism, the location of the event and the acceleration mechanism of the cosmic rays (CRs) that are responsible for the gamma-rays emission. Considering the hard spectrum of the Fermi bubbles, the emission may be generated by hadronic CRs energy losses. In such scenarios, hadronic CRs are transported via starburst or active galactic nucleus winds (Crocker & Aharonian 2011; Mou et al. 2014; Crocker et al. 2015; Mou et al. 2015). The wind velocities in these models range from a few hundred of km s\(^{-1}\) to a few thousand of km s\(^{-1}\) and the timescale for the bubbles to be formed is between \( \sim 10 \text{ Myr} \) to 1 Gyr.

Alternatively, the Fermi bubble emission could also be produced by leptonic CRs energy losses, with such leptons first being transported via an active galactic nucleus jet (Guo & Mathews 2012; Yang et al. 2012, 2013; Yang & Ruszkowski 2017; Guo 2017). For these models, the short cooling time of electrons implies that the age of the Fermi bubbles should be no more than a few Myr. Alternatively, these CRs leptons may be accelerated near the gamma-rays production site (Cheng et al. 2011; Sarkar et al. 2017; Mertsch & Petrosian 2019).

Even if the hadronic wind models exhibit a much lower velocity than the leptonic jet models the majority of proposed models assume a supersonic velocity above \( \sim 500 \text{ km s}^{-1}\). However, UV absorption line observations of cold clouds in
the Fermi bubbles, from low to high Galactic latitudes, show velocities ranging from \( \sim 100 - 300 \) km s\(^{-1}\) and with a smooth deceleration (Bordoloi et al. 2017; Karim et al. 2018; Lockman et al. 2020; Ashley et al. 2020; Cashman et al. 2021; Sofue 2022). This last feature contradicts the supersonic wind model for which a shock should be seen and then produce strong perturbations in the velocity profile.

Small Galactic outflow velocities are consistent with expectations for a thermally driven outflow (Parker 1958, 1965; Chamberlain 1965). This model is motivated from considerations of the momentum transport equation, which provides two possible solutions, a transonic and a subsonic one. The transonic description has previously been applied in galactic outflow models (Holzer & Axford 1970; Chevalier & Clegg 1985; Everett & Murray 2007) and galactic fountain models (de Avillez & Breitschwerdt 2004; Bustard et al. 2018; Chan et al. 2021). The subsonic description is less explored, with only stability analysis of such outflows having been made Fichtner (1997).

Following the first UV absorption line observations of cold clouds expanding in the Fermi bubbles, Taylor & Giacinti (2017) proposed an alternative where CRs both diffuse and are advected within a Galactic breeze. The subsonic profile that Taylor & Giacinti (2017) used was expressed as an analytic, divergence-free outflow velocity profile. This outflow with pre-accelerated hadronic CRs at its base was launched from the GC, subsequently producing \( \gamma \)-ray emission via proton-proton interactions with the diffuse ambient gas out in the halo region. Here, we investigate this model further by relaxing the divergence-free assumption for the subsonic outflow by using a hydrodynamics code. The velocity profile thus produced is used in the CR transport code, taking into account advective processes.

The paper is structured as follows: in section 2 the Galactic hydrodynamical model and the gravitational potential are introduced, as well as the numerical setup. Section 3 described the transport equation for hadronic CRs and the computational grid. The subsequent results are presented in section 4 and the conclusions and outlooks are given in section 5.

\section{Galactic Outflow Model}

To simulate the launching region and propagation of an outflow into the Galactic halo region, a hydrodynamic description has been simulated using the PLUTO code (Mignone et al. 2007). This numerical scheme solves the mass and momentum conservation equations throughout the computational grid domain,

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = S_\rho, \]  

\[ \frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v} + p \mathbf{I}) = -\rho \nabla \Phi_{\text{eff}}. \]

In these expressions, \( \rho \), \( \mathbf{v} \) and \( p \) are the mass density, velocity and thermal pressure of the gas in the Galaxy, respectively. \( \mathbf{I} \) is the unitary tensor. The terms \( S_\rho \) represent the injected mass and \( \Phi_{\text{eff}} \) is the effective gravitational potential (see section 2.1.4) determined by first calculating the total gravitational potential, \( \Phi \). Since an isothermal gas temperature is adopted (see section 2.3), here the energy conservation equation has been omitted. Details about the computational grid are provided in section 2.3.

\section{Galactic Gravitational Potential}

The total Galactic gravitational potential, \( \Phi \), results from the sum of three components, a bulge (\( \Phi_b \)), disc (\( \Phi_d \)), and dark matter halo (\( \Phi_{\text{DM}} \)) such that

\[ \Phi = \Phi_b + \Phi_d + \Phi_{\text{DM}}. \]  

\[ \Phi_b = \sum_{i=1}^{2} \frac{G M C_i}{\sqrt{r^2 + r_C^2}}, \]  

where \( r \) is the spherical radius and \( M C_1, M C_2, r_C_1 \) and \( r_C_2 \) are given in table 1.

\subsection{The bulge potential}

The central bulge potential (dot-dashed green line in figure 1), \( \Phi_b \), is based on Flynn et al. (1996) and is described by

\[ \Phi_b = \sum_{i=1}^{2} \frac{G M C_i}{\sqrt{r^2 + r_C^2}}, \]  

where \( r \) is the spherical radius and \( M C_1, M C_2, r_C_1 \) and \( r_C_2 \) are given in table 1.

\subsection{The disc potential}

The disc potential (dotted blue line in figure 1), \( \Phi_d \), is based on Flynn et al. (1996) which is a three component Miyamoto-
Table 1. List of parameters for the Galactic gravitational potential model.

| Component | Parameter | Value |
|-----------|-----------|-------|
| $\Phi_b$  | $r_{C_1}$ | 2.7 kpc |
| $M_{C_1}$ | 6.0 x 10^9 $M_\odot$ |
| $r_{C_2}$ | 0.42 kpc |
| $M_{C_2}$ | 3.2 x 10^10 $M_\odot$ |
| $\Phi_d$  | $b$       | 0.3 kpc |
| $a_1$     | 5.81 kpc  |
| $M_{D_1}$ | 1.32 x 10^3 $M_\odot$ |
| $a_2$     | 17.43 kpc |
| $M_{D_2}$ | 5.8 x 10^16 $M_\odot$ |
| $a_3$     | 34.86 kpc |
| $M_{D_3}$ | 6.6 x 10^9 $M_\odot$ |
| $\Phi_{DM}$ | $r_s$ | 21.5 kpc |

The Nagai potential (Miyamoto & Nagai 1975) given by

$$\Phi_d = \frac{\sum_{i=1}^{3} GM_{D_i}}{\sqrt{R^2 + (a_i + \sqrt{z^2 + b_i})^2}},$$  \hspace{1cm} (5)

where $R$ and $z$ are the cylindrical coordinates and $M_{D1}$, $M_{D2}$, $M_{D3}$, $a_1$, $a_2$, $a_3$ and $b$ are given in table 1.

2.1.3 The dark matter halo potential

The dark matter halo potential (dashed orange line in figure 1), $\Phi_{DM}$, is given by a Navarro-Frenk-White (NFW) profile (Navarro et al. 1996),

$$\Phi_{DM} = -\frac{GM_{200}}{r_s f(c_{200})} \ln \left(1 + r/r_s\right),$$  \hspace{1cm} (6)

where the function $f(c_{200}) = \ln (1 + c_{200}) - c_{200}/(1 + c_{200})$, $M_{200} = 2 \times 10^{12} M_\odot$ (Taylor et al. 2016) and $c_{200}$ is the concentration parameter defined as $c_{200} = r_{200}/r_s$ where $r_{200} = 258$ kpc and $r_s = 21.5$ kpc is the scale radius.

2.1.4 The effective Galactic potential

Observations of the Milky Way’s rotation curve within the disc indicate velocities of ~200 km s$^{-1}$ beyond 2 kpc from the GC (Sofue 2013; Bhattacharjee et al. 2014). Eqs. (1) and (2) have then been solved in a rotating frame since such a Galactic rotational velocity value cannot be neglected for a Galactic breeze model, for which the outflow velocity is similar in magnitude to the Galactic rotation velocity. In the rotating frame, the effective Galactic potential, $\Phi_{eff}$, used in Eq. (2) is of the form,

$$\Phi_{eff} = \Phi + \frac{R}{2} \left( \frac{d\Phi}{dR} \right),$$  \hspace{1cm} (7)

2.2 1D spherical Galactic outflow

Some intuition on the outflow evolution can be found through the consideration of an 1D spherically symmetric outflow (Parker 1958, 1965; Chamberlain 1965; Lamers & Cassinelli 1999). For this case, mass flux conservation leads to the relation

$$\dot{M} = 4\pi r^2 \rho(r) v(r),$$  \hspace{1cm} (8)

where $\dot{M}$ is defined as the mass loss rate. The momentum flux conservation equation, assuming an isothermal, steady-state evolution, leads to the relation

$$\frac{dv}{dr} + \frac{c_s^2}{\rho} \left( \frac{d\rho}{dr} \right) = 0,$$  \hspace{1cm} (9)

where $c_s$ is the thermal velocity. By differentiating Eq. (1) to get the density gradient and substituting it into Eq. (2) the following expression is obtained

$$\frac{1}{v} \frac{dv}{dr} = 1 - \frac{(2c_s^2 - v^2)}{v^2} \frac{d\Phi}{dR}.$$  \hspace{1cm} (10)

The numerator on the right-hand side of this expression goes to zero when $v^2 = 2c_s^2$. The radius where this occurs is called the critical radius, $r_c$. Beyond $r_c$, for a positive numerator, a transonic outflow will accelerate while a subsonic outflow will decelerate. The behavior of a transonic outflow and its different solutions have been studied in a gravitational potential of a cold dark matter halo (Tsuchiya et al. 2013; Igarashi et al. 2014, 2017).

The total effective potential model adopted for the Galaxy is not entirely spherically symmetric due to both the disc component and the Galactic rotation. These effects have an influence on the determination of the value of $r_c$. This value is important since it determines the subsequent velocity evolution which is discussed in the following section.

2.3 Galactic gas temperature and density profile

As discussed at the beginning of section 2, the hydrodynamic equations (see Eq. (1) and (2)) are considered for an isothermal gas. Indeed, observations of the Galactic halo gas do not show strong temperature fluctuations (Tumlinson et al. 2017).

Based on Watkins et al. (2019), the normalisation for the Galactic potential, $\Phi$, has been adopted with a value at the upper end of the allowed range (see Fig. 1 and section 2.1). In order to maximise the outflow velocity, while maintaining the existence of $r_c$ beyond the radius where the CRs are injected, a gas temperature of $kT \approx 500$ eV, $c_s \approx 250$ km s$^{-1}$, is adopted. By choosing these values for $\Phi$ and $c_s$ implies $r_c \approx 1$ kpc (see section 2.2).

For the initial gas density setup, a hydrostatic density distribution is assumed, dictated by the Galactic potential, $\Phi$, and the single gas temperature with thermal velocity, $c_s$. This initial spatial gas number density distribution can be expressed as,

$$n_{halo} = n_{10kpc} \exp \left( -\frac{\Phi}{c_s^2} \right),$$  \hspace{1cm} (11)

where $n_{10kpc}$ is a normalisation constant. Its value has been fixed at $n_{10kpc} = 10^{-3}$ cm$^{-3}$ in order to be compatible with the observational values provided in a range of 10-100 kpc (Gupta et al. 2017; Martynenko 2022). Fig. A1 in Appendix A shows the hydrostatic gas number density distribution adopted in this paper.

2.4 Numerical setup

As shown in section 2.2, Eq. (10) implies that an outflow driven by thermal gas pressure can reach a given velocity...
at \( r_c \) for a particular velocity \( v_0 \) at the launching zone \( r_0 \). For the simulations, an outflow reaching a Mach number of \( M = 0.85 \) at \( r_c \) has been chosen. Considering \( r_c \approx 1\) kpc, given in section 2.3, Eq. (10) is solved numerically to provide \( v_0 \). The inner radius, \( r_0 \), is fixed to be \( r_0 = 300 \) pc. The thermal pressure at \( r_0 \) is then defined as \( P_0 = \rho_0 c_s^2 \). The computational grid has been setup as a 2D spherical grid \((r, \theta)\). A logarithmic grid is used with 256 bins in the \( r \)-direction and uniform grid spacing in the \( \theta \)-direction with 90 bins. The outflow is launched at \( r_0 \) and the outer radial boundary is set to an absorbing boundary condition, at 300 kpc. With this setup, the outflow does not reach the outer boundary during the simulation time of 300 Myr. The system reaches steady state at smaller distances at earlier times than this. Both the inner and outer boundary in the \( \theta \)-direction have been set to reflective. The simulation domain covers a single hemisphere, with \( \theta \) ranging from 0 to \( \pi/2 \).

3 CRS TRANSPORT MODEL

The transport of CRs through an outflow is described, in its conservative form, by the following equation,

\[
\frac{\partial f}{\partial t} = \nabla \cdot (\mathbf{D} \nabla f - \mathbf{v} \cdot \nabla f) + \frac{1}{p^2} \frac{\partial}{\partial p} \left[ (\nabla \cdot \mathbf{v}) \frac{p^3}{3} f \right] - \frac{f}{\tau_{\text{loss}}} + \frac{Q}{p^2} \tag{12}
\]

where \( f = \frac{dN}{d\mathbf{x}dp} \) is the cosmic ray phase space density and \( N \) is the number of particles. \( D \) is the spatial diffusion coefficient, \( \mathbf{v} \) is the outflow velocity, \( p \) is the CRs momentum, \( \tau_{\text{loss}} \) is the energy loss time scale for \( pp \) collisions and \( Q \) is the CRs spectrum injected per unit time and per unit volume (see section 3.2). The first term on the right hand side of Eq. (12) represents the spatial diffusion of CRs through the outflow depending on the turbulence and strength of the magnetic field (see section 3.1) and spatial advection which acts to suppress the CRs flux. The second term represents momentum advection which moves the CRs to lower energies as they are transported in the expanding advective outflow. The fourth term is the CRs loss rate which is the rate at which the CRs lose their energy. A hadronic CRs experiences energy losses through inelastic \( pp \) collisions (Gabici et al. 2007) in the halo region with a loss time scale \( \tau_{\text{loss}} \approx 60 \) Gyr, on a halo distance scale of 10 kpc.

For the results (see section 4.2), the CRs number density, \( n_{\text{CRs}} \), will be presented instead of \( f \). In order to determine \( n_{\text{CRs}} \) from \( f \) which the transport equation provides, the momentum dependence of the phase space distribution is integrated out,

\[
n_{\text{CR}} = \int_{p_{\text{min}}}^{p_{\text{max}}} 4\pi f p^2 dp = \int_{p_{\text{min}}}^{p_{\text{max}}} \frac{dN}{d\mathbf{x}dp} dp. \tag{13}
\]

Here \( p_{\text{min}} = 10 \) GeV/c and \( p_{\text{max}} = 30 \) GeV/c are the minimum and maximum momentum for the injected CRs for the results presented in section 4.2. This range has been chosen to coincide with one of the selected ranges by Ackermann et al. (2014) for the \( \gamma \)-ray observations of the Fermi bubbles.

3.1 Diffusion coefficient

The diffusion coefficient determines the distance that a CRs, on average, can travel through ambient magnetic fields until its momentum vector has changed significantly (~1 rad. in angle). For the purpose of the calculations, a simple commonly used expression for the diffusion coefficient is adopted (Jokipii 1966; Schlickeiser 1989), which expressed as a length-scale is,

\[
\frac{D}{c} = 0.1 \left( \frac{p}{10 \text{ GeV/c}} \right)^{2-\gamma} \text{pc}, \tag{14}
\]

where \( c \) is the speed of light and \( \gamma = 5/3 \) is the Kolmogorov turbulence power-spectrum slope.

3.2 Injection and CRs spectrum

The injection site for the CRs source is assumed to be at the base of the outflow at \( r_0 \). The volumetric injection rate \( Q \) is defined as,

\[
Q = \frac{d\dot{N}}{d^3xdp}, \tag{15}
\]

where \( \dot{N} \) is the number of particles injected per unit time.

A continuous injection spectrum has been used such that \( \frac{d\dot{N}}{dp} \propto p^{-\alpha} \exp(-p/p_{\text{max}}) \), with \( \alpha = 2 \) representative of diffusive shock acceleration (Bell 1978), and \( p_{\text{max}} = 10^7 \) GeV/c. The total injected luminosity is expressed as

\[
L_{\text{CR}} = c \int_{p_{\text{min}}}^{p_{\text{max}}} p \frac{d\dot{N}}{dp} dp, \tag{16}
\]

The total injected luminosity has been set to \( L_{\text{CR}} = 6 \times 10^{41} \) erg s\(^{-1}\) which determines the value of \( \dot{N} \). This value has been chosen to match with the fitting range for the energy flux provided by the observations of the Fermi bubbles (Ackermann et al. 2014).

3.3 Numerical setup

Based on a 2D differencing scheme (Rodgers-Lee et al. 2017, 2020), the temporal evolution of \( f \), using a steady-state subsonic velocity solution for the advection terms, is obtained for a timescale of 300 Myr. The grid adopted in these calculations has a cylindrical \((R, z)\) geometry with logarithmic spacing for both \( R \) and \( z \) grids with 350 bins. The outflow velocity, \( \mathbf{v} \), obtained from the hydrodynamic simulations (see section 2) has been used as an input for Eq. (12). Considering this velocity profile (see section 2.4) the inner boundary has been set up at 300 pc, and the outer boundary at 100 kpc. The CRs are injected close to the inner boundary. The momentum grid is logarithmically spaced with 5 bins ranging from 10 – 30 GeV/c. The simulations have been done for one quadrant only. The results presented here have subsequently been reflected into the other quadrants.

4 RESULTS

4.1 Hydrodynamic outflow

Fig. 2 shows the 2D velocity profile of the subsonic outflow in both the \( R \) and \( z \)-directions for \( t = 300 \) Myr. The Galactic potential adopted in this paper (see section 2.1), in combination with a temperature of \( kT \approx 500 \) eV for the halo region, gives two roots for Eq. (10). Once injected at the inner radius the
gas first decelerates until reaching a distance of $\sim 0.45$ kpc and then accelerates. This acceleration continues outwards up to $r_1 \approx 1$ kpc (red region in Fig. 2), reaching a velocity of $v \approx 210$ km s$^{-1}$, after which the gas then decelerates continuously (as shown by the orange to blue regions in Fig. 2). The outflow is collimated by the gas distribution resulting from the Galactic potential adopted (as shown by the orange and green region). As discussed in section 2.2, the asphericity of the potential results in a conic shape for the outflow. The conic shape then extends to a bubble shape as it decelerates (blue light region in Fig. 2). It is found that the centrifugal force due to Galactic rotation has only a minor effect on the results. It reduces the gravitational force acting on the outflow at larger distances from the rotation axis slightly and mildly enhances the extension of the outflow velocity in the $R$ direction.

The continuous deceleration along increasing Galactic latitude gives the following velocities: $v(z = 3 \text{ kpc}) \approx 120$ km s$^{-1}$, $v(z = 5 \text{ kpc}) \approx 85$ km s$^{-1}$, $v(z = 7 \text{ kpc}) \approx 70$ km s$^{-1}$ and $v(z = 10 \text{ kpc}) \approx 53$ km s$^{-1}$. These results appear compatible with observations of UV absorption lines of OI, AI, CII, CIV, SiII, SiIII, SiIV and other species provided by Bordoloi et al. (2017) for the Local Standard of Rest velocity. However, the velocities given above are lower than the values inferred from similar UV absorption line studies (Karim et al. 2018) for the South Fermi bubble. It should be noted that an asymmetry between the North and South Fermi bubble exists, potentially related to different density distributions in the two hemispheres (Sarkar 2019). More recent observational results for both North and South Fermi bubbles provided by Ashley et al. (2020) give a outflow profile similar to Karim et al. (2018) but with a somewhat faster velocity, by a factor $\sim 10\%$.

4.2 CRs density map

Here the results related to the CRs propagation through the outflow velocity region described in section 4.1 are presented. Advection and diffusion are the two terms in the transport equation (Eq. (12)) which compete to dictate the resultant CRs transport. The diffusion mechanism can be ignored if the outflow velocity is high enough, and one is considering low energy ($< 10$ GeV) CRs (see Eq. 14). However for the case of a Galactic breeze, $v$ is sufficiently small such that both terms play an important role in dictating the resultant CRs spatial distribution. This effect can be seen in Fig. 3, which shows a 2D plot of the CRs number density distribution in the Galaxy produced with the model. In the vicinity of the GC, where the outflow velocity is the highest (as shown in by the blue to green region in Fig. 3), advection is the dominant transport mechanism. In this region, due to collimation effects, the CRs propagate mainly along the $z$-direction (orange region in Fig. 3). The velocity difference in the $R$ and $z$-direction is less pronounced as the outflow decelerates. Subsequently, the bubble-shape becomes more spherical in shape at higher latitudes.

4.3 Gamma-rays emission map

Inelastic CRs collisions with ambient gas in the Galactic halo results in the creation of charged and neutral pions. The dominant decay mode for neutral pions is into two photons (Particle Data Group et al. 2020). A photon produced by such a collision obtains $\sim 10\%$ of the initial CRs proton energy. Therefore, for the 10-30 GeV CRs energy range considered, photons with energy $E_\gamma = 1 - 3$ GeV are produced. The resulting gamma-rays energy flux density, $dF_\gamma$, from each emitting cell of volume $dV$ on the computational grid seen by an observer is then expressed as

$$dF_\gamma = \frac{dL_\gamma}{4\pi d^2} = \frac{1}{4\pi d^2} \frac{e_{\text{CR}}}{\tau_{\text{loss}}} dV,$$

where $d$ is the distance between the emitting cell and the observer. The position of the observer from the GC has been fixed at 8 kpc (Gillessen et al. 2017). The CRs energy density, $e_{\text{CR}}$ is expressed as

$$e_{\text{CR}} = \int_{p_{\text{min}}}^{p_{\text{max}}} 4\pi f p^3 dp.$$

The energy flux from all of the cells contained along the
The skymap of the gamma-rays energy flux density is shown in Fig. 4a for $E_\gamma = 1 - 3$ GeV (Fig. 4b is for $E_\gamma = 1 - 3$ TeV, see section 4.3.1). The simulated subsonic velocity profile in combination with $L_{CR} = 6 \times 10^{41}$ erg s$^{-1}$ produces bilobal gamma-rays emission, with a pronounced pinch at low Galactic latitudes. From observations, the height of the Fermi bubbles is $\sim 10$ kpc, corresponding to $\sim 50^\circ$ for an observer at $\sim 8$ kpc.

The brightness of the gamma-rays energy flux produced appears broadly consistent with Fermi-LAT observations. However, the width of the observed Fermi bubbles, estimated to be around $20^\circ$ from the central axis (Ackermann et al. 2014) are narrower than the simulation results shown here, which extend to a width of $30^\circ$. This difference originates from the assumptions in the adopted setup. Specifically, both the magnitude of the CRs diffusion coefficient (see Eq. 12), and the isothermal gas temperature, collectively dictate the subsequent lobe width.

4.3.1 Predictions for CTA and SWGO

The Cherenkov Telescope array (CTA, Acharya et al. 2018) and the Southern Wide-field gamma-rays Observatory (SWGO, Abreu et al. 2019), a wide field observatory that will complement CTA, are next generation ground-base gamma-rays instruments, which collectively will span an energy range from 20 GeV to 300 TeV (Abdalla et al. 2021). A simulation for the transport of $E = 10 - 30$ TeV energy CRs has been run in order to predict what future observations of the Fermi bubbles will look like if a subsonic outflow is responsible for the gamma-rays emission. The gamma-rays emission map produced by the CRs is shown in Fig. 4b. These simulations are done with the same setup, for both the hydrodynamic outflow simulation (see Section 2.4) and the CR transport code (see Section 3.3). Considering the adopted subsonic velocity profile and the high CRs energies, diffusion plays a more prominent role (see Eq. (14)). Compared to the lower energy gamma-rays emission map shown in Fig. 4b, the gamma-rays distribution is wider and reaches a slightly lower height. This difference is due to the energy dependence of the diffusion coefficient adopted, which introduces energy dependent transport effects. For a height of $\sim 50^\circ$ the predicted energy flux observed, according to the subsonic model presented here, should be between $8 - 10 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

Returning to the comparison between the Fermi-LAT data and Galactic breeze simulations results, in Fig. 5 a direct comparison is made between the simulations and data provided by the Fermi-LAT collaboration (Ackermann et al. 2014) for latitudes from $b = 30^\circ - 50^\circ$. The blue line represents the energy flux provided by the simulations for a subsonic outflow. The red error bar ranges come from the data defined with the GALPROP CR propagation and interactions code (Vladimirov et al. 2011) as templates. The red shaded regions were computed from uncertainties of different models and different definitions of the templates. Both the red error bar ranges and the red shaded regions are from Ackermann et al. (2014). At latitudes between $30^\circ < b < 40^\circ$ and $40^\circ < b < 50^\circ$, (for $-15^\circ < l < 15^\circ$), the energy flux is broadly compatible with the observations, although as already noted previously, beyond a longitude of $15^\circ$ the energy flux no longer falls within the red shaded region due to the broader width of the simulated lobes.

5 CONCLUSIONS AND OUTLOOK

Following on from an earlier investigation (Taylor & Giacinti 2017) into the subsonic outflow origin of the Fermi bubbles, a hydrodynamical outflow simulation has been carried out here. The outflow velocity profile provided by the hydrodynamic simulation is then used as part of a 2D CR transport code description. CRs transported by the outflow into the Galactic halo region subsequently undergo inelastic pp energy loss interactions with the low density hot ambient gas present. These energy loss interactions give rise to spatially dependent gamma-rays emission. A comparison of this emission is made, for a specific photon energy range of $1 - 3$ GeV, with Fermi bubble observations data provided by the Fermi-LAT satellite. Following these results a higher energy emission map prediction is provided, in the $1 - 3$ TeV energy range of relevance for next generation instruments (CTA/SWGO).

The hydrodynamic simulation results presented in this paper reveal that the Galactic breeze naturally collimates, propagating predominantly in the direction orthogonal to the Galactic plane. This outflow subsequently develops a conical shape, which eventually become lobe-like in shape at large distances. The continuous deceleration of the outflow beyond the critical radius appears consistent with UV absorption line observations of cold clouds within the Fermi bubble region (Bordoloi et al. 2017; Ashley et al. 2020). A comparison of the gamma-rays skymap emission produced by the CRs energy losses show that these are broadly compatible with the Fermi bubble observations provided by Ackermann et al. (2014). This result reinforces the idea that a Galactic breeze can reproduce the observed Fermi bubble structures.

Fundamentally, the present limited knowledge about the nature of the Galactic halo region (ie. the gas density and temperature, and the shape of the Galactic potential) limits our ability to describe gas and CRs transport through this region. Of particular concern are Galactic halo magnetic fields, which have not been considered explicitly in the transport description used here. However, these fields certainly play an intrinsic role in CRs diffusion, and likely also play a role in a more complete magneto-hydrodynamic description of the gas outflow. Furthermore, the presence and strength of these fields may well underlie the existence of the Fermi bubbles. Introducing a Galactic magnetic field description into the simulations presented here is, therefore, a natural next step to consider in the development of a more realistic outflow scenario. New insights about the Galactic halo magnetic field have started to be provided from synchrotron emission observations over the last decade (Dobler & Finkbeiner 2008; Dobler 2012; Planck Collaboration et al. 2013; Carretti et al. 2013). Analytic models have recently inferred magnetic field strengths of several $\mu$G within these regions to explain this synchrotron emission (Shaw et al. 2022).

Further observations probing the nature of the halo environment are needed in order to provide a better constraint on the Galactic potential and temperature for the gas throughout the Galaxy. Observations of cold clouds in the Fermi bubbles, at $2 - 3$ kpc from the GC, give a velocity outflow
Gone with the breeze

Figure 4. $\gamma$-ray emission maps produced with a subsonic outflow for $t = 300$ Myr. The dashed black lines contouring the different colors represent the upper limit for each color range. **Left:** The emission is produced by photons with energy ranging from 1 to 3 GeV. **Right:** The emission is produced by photons with energy ranging from 1 to 3 TeV. It is important to note that colour bar limits are not the same for the two plots.

Figure 5. The photons energy flux produced by the gamma-rays emission is plotted as a function of Galactic longitude for different latitude ranges. The blue line represent the energy flux provided by the simulations for a subsonic outflow presented in this paper. The error bar ranges and the shaded red region are provided by the Fermi-LAT observational results (Ackermann et al. 2014). The red error bars represent the energy flux determined from observations of the Fermi bubbles. The shaded red region has bee computed from uncertainties of different models and different possible templates. **Left:** The photons energy flux is compared with Fermi-LAT data for $b = 30^\circ - 40^\circ$. **Right:** The photons energy flux is compared with Fermi-LAT data for $b = 40^\circ - 50^\circ$.

of $\sim 330$ km s$^{-1}$ (Ashley et al. 2020). Such a value is hardly reachable for an isothermal subsonic description considering the fitting range for the Galactic gravitational potential provided by Watkins et al. (2019). On the other hand, the apparent smooth deceleration of the gas observed with increasing latitude, is compatible with a subsonic outflow scenario. A single temperature model, therefore, may provide an insufficiently accurate account of the gas velocity evolution. Indeed, evidence for a transition between a hot bulge and an even hotter halo ($\sim 1$ keV) out at larger distances (Das et al. 2019a,b, 2021), motivates the consideration of a more complex temperature profile than the one considered here.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.
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APPENDIX A: HYDROSTATIC DENSITY DISTRIBUTION

In Fig. A1 the hydrostatic density distribution, \( n_{\text{halo}} \), obtained from an evaluation of Eq. 11 is shown. It is noted that \( n_{\text{halo}} \) is compatible, in the 10-100 kpc distance range, with the constraints from the ram pressure stripping of satellite galaxies around the Milky Way Martynenko (2022).
Figure A1. The hydrostatic number density distribution as a function of $z$ for gas in the Galactic halo.