Role of Cosmic Ray Streaming and Turbulent Damping in Driving Galactic Winds

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ABSTRACT
Large-scale galactic winds driven by stellar feedback are one phenomenon that influences the dynamical and chemical evolution of a galaxy, redistributing material throughout the circumgalactic medium. Non-thermal feedback from galactic cosmic rays (CRs) – high-energy charged particles accelerated in supernovae and young stars – can impact the efficiency of wind driving. The streaming instability limits the speed at which they can escape. However, in the presence of turbulence, the streaming instability is subject to suppression that depends on the magnetization of turbulence given by its Alfvén Mach number. While previous simulations that relied on a simplified model of CR transport have shown that super-Alfvénic streaming of CRs enhances galactic winds, in the present paper we take into account a realistic model of streaming suppression. We perform three-dimensional magnetohydrodynamic simulations of a section of a galactic disk and find that turbulent damping dependent on local magnetization of turbulent interstellar medium (ISM) leads to more spatially extended gas and CR distributions compared to the earlier streaming calculations, and that scale-heights of these distributions increase for stronger turbulence. Our results indicate that the star formation rate increases with the level of turbulence in the ISM. We also find that the instantaneous wind mass loading is sensitive to local streaming physics with the mass loading dropping significantly as the strength of turbulence increases.

Key words: cosmic rays – galaxies: evolution – cosmic rays – galaxies: star formation

1 INTRODUCTION
The baryon-to-halo-mass ratio in galaxies is considerably lower than the cosmological average (Bell et al. 2003). At $L_\star$, roughly the Milky Way (MW) luminosity, about 20 percent of baryons are accounted for when matching the observed luminosity to the halo mass function, while at higher or lower luminosities the discrepancy widens (Guo et al. 2010). Additionally, absorption lines in background quasars provide evidence for the pollution of the intergalactic medium (IGM) with the products of stellar evolution formed only deep in the galactic potential well, such as dust (e.g., Menard & Fukugita 2012) and metals (e.g., Songalia 2001), up to at least redshift $z = 6$, suggesting that galactic baryons were expelled due to feedback.

At higher luminosities than $L_\star$, feedback from active galactic nuclei (AGN) dominates (e.g., Croton et al. 2006). For lower luminosities, stellar feedback can drive galactic outflows, pushing and redistributing material, significantly affecting the dynamical and chemical evolution of galaxies (Larson 1974; White & Rees 1978; Dubois & Teyssier 2010). Indeed, galactic winds have been observed in galaxies that have had recent and significant star formation (Veilleux et al. 2005), driving gas out at a rate of 0.01 to 10 times the star formation rate (SFR) (Bland-Hawthorn et al. 2007).

The stellar feedback which drives winds is likely the result of several mechanisms combining in a non-linear manner (e.g., Agertz et al. 2013). A detailed understanding of the exact mechanisms and their complex interactions remains uncertain, as many processes operate below the grid scale of simulations in galactic and cosmological simulations (Somerville & Davé 2015).

Mechanisms used to explain winds are thermal (Chevalier & Clegg 1985; Joung et al. 2009) and momentum (Kim et al. 2016) feedback from supernovae (SN), as well as radiation pressure from massive stars (Murray et al. 2005, 2011; Hopkins et al. 2012). Galactic cosmic rays (CRs), originat-
ing from shock acceleration in SN remnants (see Bykov et al. 2018) and winds from massive stars (see Bykov 2014) can also play a significant role in launching galactic winds. In the MW, the CR energy density is in rough equipartition with the turbulent and magnetic field energy densities (e.g., Boulanger & Cox 1990). Additionally, Fermi γ-ray observations of starburst galaxies M82 and NGC 253 suggest CR energy densities two orders of magnitude above the MW values (Paglione & Abrahams 2012; Yoast-Hull et al. 2013). These two findings hint at the importance of CRs in the evolution of galaxies. Theoretical considerations suggest that CRs can play important role in driving gas in galactic winds (Everett et al. 2008; Breitschwerdt et al. 1991). Three-dimensional hydrodynamical (Uhlig et al. 2012; Booth et al. 2013; Salem & Bryan 2014) and magneto-hydrodynamical (MHD) (Hanasz et al. 2013; Girichidis et al. 2016; Pakmor et al. 2016) simulations have demonstrated that CRs indeed influence the generation of global outflows and the local structure of the interstellar medium (ISM). The exact properties of the simulated outflows depend sensitively on how CR transport is modeled (Simpson et al. 2016; Ruszkowski et al. 2017; Faber et al. 2018).

In the self-confinement model of CR transport, CRs propagating in one direction along the magnetic field in the galaxy generate Alfvén waves that scatter CRs back, thus amplifying the waves. This process is called the streaming instability and in the absence of wave dissipation it was shown to reduce the CR bulk streaming speed $u_s$ (relative to the gas) to the Alfvén speed $u_A$ (see Kulsrud & Pearce 1969). This effectively couples the plasmas with the CRs. In terms of galactic winds this means that the flux of CRs can transfer its momentum to the wind material.

If the dissipation of Alfvén waves is present, the streaming instability can be still present and the coupling of the waves and the wind is decreased. Historically, the damping of the Alfvén waves in the context of streaming instability suppression is associated with the ion-neutral linear damping process (Kulsrud & Pearce 1969). Therefore the process is not efficient for the highly ionized matter expected to form galactic winds. However, it was noted in Yan & Lazarian (2002) that the streaming instability can be suppressed by turbulence. Farmer & Goldreich (2004) proposed a model for trans-Alfvénic strong MHD turbulence, corresponding to the Alfvén Mach number $M_A = u_s/u_A$, where $u_s$ is the injection velocity at the turbulence injection scale $L$. This study was generalized for the arbitrary $M_A$ in Lazarian (2016), where it was shown that the damping significantly changes with $M_A$. Moreover, the latter study showed that the scaling for the dependences of the damping of the streaming instability for $M_A < 1$ is different for high energy CRs that induce waves that are non-linear damped by the weak Alfvénic turbulence (see Lazarian & Vishniac 1999; Galtier et al. 2000) that spans the range from $LM_A^2$ to $L$ and the lower energy cosmic rays that induce waves that are non-linearly damped by the strong MHD turbulence existing at the scales less than $LM_A^2$. Note, that the terms weak and strong turbulence do not reflect the amplitude of Alfvénic perturbations, but the strength of non-linear interactions (see Brandenburg & Lazarian 2013).

Observations of the MW suggest that the case of $M_A < 1$ is the most appropriate for the turbulence at high galactic latitudes corresponding to the action of the galactic wind (see Kandel et al. 2018). The magnetically dominated, i.e. low $\beta$ medium is also expected for the galactic wind environment. Therefore we do not consider the non-linear Landau damping (Zweibel 2013) that may be important for the damping of Alfvén waves in high $\beta$ media. The turbulent damping of the streaming instability is a robust process that depends only on the turbulence properties and does not depend on plasma $\beta$. Our present study is focused on studying the consequences of this process for the generation and the evolution of stellar winds.

The important earlier work that considered the effects of the launching of the galactic winds with CRs and taking into account the effects of the streaming instability is Ruszkowski et al. (2017). There a simple parameterization $u_s = f u_A$ was considered for the CR streaming speed in three-dimensional MHD simulations of an isolated galaxy ($f$ was assumed to be constant). In these simulations, the CR streaming generally enhances the efficiency of galactic wind driving, as the CRs can escape from dense regions and interact with more tenuous gas that is easier to accelerate. As the efficiency of wind coupling with CRs is determined by the efficiency of the turbulent damping of the streaming instability, it is essential to properly model this process. In implementing a more physically motivated model compared to that adopted by Ruszkowski et al. (2017), we use the model of turbulent damping in Lazarian (2016) and provide the more accurate description of the turbulent damping of Alfvén waves. We calculate the resulting streaming speed that depends on the local properties of the ISM and halo. We perform three-dimensional MHD simulations of a section of a MW-like galactic disk in order to investigate the effects of locally-determined CR streaming controlled by the turbulent structure of the ISM. We include magnetic fields, radiative cooling, self-gravity, and stellar feedback (star formation and SN, with thermal and CR injection). In Section 2, we describe the treatment of numerical methods and physical models, while in Section 3 we discuss results, with conclusions in Section 4.

### 2 METHODS

We run simulations with the adaptive mesh refinement MHD code FLASH 4.2 (Fryxell et al. 2000; Dubey et al. 2008) using a directionally unsplit staggered mesh (USM) solver (Lee & Deane 2009; Lee 2013), including CR physics (Yang et al. 2012; Ruszkowski et al. 2017; Faber et al. 2018), in an elongated box of dimensions $2 \times 2 \times 40$ kpc$^3$.

We solve the MHD equations with a two-fluid model (Salem & Bryan 2014; Ruszkowski et al. 2017), including both thermal gas and ultra-relativistic CR fluid (composed of protons) characterized by adiabatic indices $\gamma = 5/3$ and $\gamma_{cr} = 4/3$, respectively. We use a mean CR Lorentz factor $\gamma_{rel} = 3$, and a slope $s = 4.5$ for the CR distribution function in momentum, which are typical values for galactic CRs.

We include CR advection, dynamical coupling between CRs and thermal gas, CR streaming along the magnetic field lines and the associated heating of gas by CRs, gas

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1 $\beta$ is the ratio of the gaseous pressure to the magnetic pressure.
self-gravity, radiative cooling, star formation, and evolve the following equations:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}_g) = -\dot{m}_{\text{form}} + f_s \dot{m}_{\text{feedback}} \tag{1}
\]

\[
\frac{\partial \rho \mathbf{u}_g}{\partial t} + \nabla \cdot \left( \rho \mathbf{u}_g \mathbf{u}_g - \frac{\mathbf{B} \mathbf{B}}{4\pi} \right) + \nabla p_{\text{tot}} = \rho \mathbf{g} + \dot{p}_{\text{SN}} \tag{2}
\]

\[
\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{u}_g \times \mathbf{B}) = 0 \tag{3}
\]

\[
\frac{\partial e}{\partial t} + \nabla \cdot \left( (e + p_{\text{tot}}) \mathbf{u}_g - \frac{\mathbf{B} \mathbf{B} - \mathbf{u}_g \mathbf{u}_g}{4\pi} \right) = \rho \mathbf{u}_g \cdot \mathbf{g} - \nabla \cdot F_{\text{cr}} - C + H_{\text{SN}} + H_{\text{CR}} \tag{4}
\]

\[
\frac{\partial e_{\text{cr}}}{\partial t} + \nabla \cdot (e_{\text{cr}} \mathbf{u}_g) = -\rho_{\text{SN}} \nabla \cdot \mathbf{u}_g - H_{\text{cr}} + H_{\text{SN}} - \nabla \cdot F_{\text{cr}} \tag{5}
\]

\[\Delta \phi = 4\pi G \rho \mathbf{b}\]

where \(\rho\) is the gas density, \(\rho_{\text{SN}}\) is the total baryon density including both the gas and stars, \(\dot{m}_{\text{form}}\) is the density sink from stellar population particle formation, \(f_s \dot{m}_{\text{feedback}}\) represents the gas density source from stellar feedback (see Section 2.3), \(\mathbf{u}_g\) is the gas velocity, \(\mathbf{B}\) is the magnetic field, \(G\) is the gravitational constant, \(\phi\) is the gas gravitational potential, \(\mathbf{g} = -\nabla \phi + g_{\text{NFW}}\) is the gravitational acceleration (the sum of gas self-gravity, stellar particle, and halo dark matter contributions to the gravitational acceleration, described in Section 2.1) where \(g_{\text{NFW}}\) is the gravity from the Navarro-Frenk-White (NFW) potential, \(p_{\text{tot}}\) is the sum of gas (\(p_h\)), magnetic, and CR (\(p_{\text{CR}}\)) pressures, \(\rho_{\text{SN}}\) is the momentum injection due to stellar winds and SN. Furthermore, \(e = \rho u_g^2 + e_g + e_{\text{cr}} + B^2/8\pi\) is the total energy density per volume (the sum of gas, CR, and magnetic, respectively), \(C\) is the radiative cooling rate per unit volume, and \(H_{\text{SN}}\) is the supernova heating rate per volume. CR advection and coupling to the gas are included using the same methods as in Ruszkowski et al. (2017) (see Yang et al. 2012, 2013; Sharma et al. 2009) with the CR streaming flux denoted by \(F_{\text{CR}}\) and an associated CR heating of the gas denoted by \(H_{\text{CR}}\). The streaming flux is \(F_{\text{CR}} = (c_s + \rho_{\text{CR}}) v_s\), with the streaming speed along the magnetic field down the CR gradient \(v_s = -\text{sgn}(\mathbf{b} \cdot \nabla c_{\text{cr}}) \approx \text{tanh}(h_{\text{CR}} \tilde{\mathbf{b}} \cdot \nabla c_{\text{cr}}/c_{\text{cr}})\), where \(\tilde{\mathbf{b}}\) is the magnetic direction vector. When damping processes are included, we write \(u_s = f u_A\), where \(f\) is a function of local gas properties (see Section 2.4). The regularization parameter \(h_c = 10 \text{ kpc} \) helps avoid prohibitively small time-steps due to discontinuities in \(F_{\text{CR}}\) near extrema of the CR energy density distribution (Sharma et al. 2009). The streaming speed is limited to 200 km/s for computational efficiency. We have tested higher ceilings finding no significant change in the results. Additionally, we sub-cycle four times over the CR streaming term to further accelerate computations.

### 2.1 Gravity

The gravitational acceleration has contributions from the gravity of gas, stellar particles, and dark matter halo vertical component. For the self-gravity of baryons, we solve the Poisson equation with the Barnes-Hut tree solver (Barnes & Hut 1986) implemented by Wunsch et al. (2018). We also include the gravitational contribution from the overall dark matter halo (Navarro et al. 1997). Since the domain is a thin slice of a galaxy, we only use the vertical component of gravity

\[g_{\text{NFW}}(z) = -GM_{200} \ln(1 + x) - x(1 + x) / [c^3 \ln(1 + c) - c(1 + c)] \tag{7}\]

where \(G\) is the gravitational constant, \(M_{200}\) is the halo virial mass, \(z\) is the height above the mid-plane, \(x = |z|/r_{200}\), \(c\) is the halo concentration parameter, and \(r_{200}\) is the virial radius. In this approximation, we assume that vertical slab is centered on the galactic center. Table 1 summarizes the parameters we use.

### 2.2 Radiative cooling

We use the Townsend cooling method (Townsend 2009) implemented as in Farber et al. (2018). The cooling function \(\Lambda(T)\) is a piecewise power law with a floor temperature of 300 K (Rosen & Bregman 1995) given in units of erg cm$^{-3}$ s$^{-1}$ by

\[
\Lambda(T) = \begin{cases} 
0 & \text{if } T < 300 \\
2.2380 \times 10^{-32} T^{-2.0} & \text{if } 300 \leq T < 2000 \\
1.0012 \times 10^{-30} T^{-1.5} & \text{if } 2000 \leq T < 8000 \\
4.6240 \times 10^{-36} T^{-2.867} & \text{if } 8000 \leq T < 10^5 \\
1.7800 \times 10^{-18} T^{-0.65} & \text{if } 10^5 \leq T < 4 \times 10^7 \\
3.2217 \times 10^{-27} T^{-0.5} & \text{if } 4 \times 10^7 \leq T,
\end{cases}
\]

where \(T\) is the gas temperature in K. This cooling function is an approximation to the radiative cooling functions in Dalgarno & McCray (1972) and Raymond et al. (1976), accurate for a gas of solar abundance that is completely ionized gas at \(T = 8000\) K. The Townsend scheme does not impose restrictions on the cooling time step.

### 2.3 Star formation and feedback

Star formation follows the approach of Cen & Ostriker (1992) (see also Tasker & Bryan 2006; Bryan et al. 2014; Salem & Bryan 2014; Li et al. 2015) where star formation occurs when all of the following conditions are met: (i) gas density exceeds \(1.67 \times 10^{-23}\) cm$^{-3}$ (Gnedin & Kravtsov 2011; Agertz et al. 2013); (ii) the cell mass exceeds the local Jeans mass; (iii) \(\nabla \cdot \mathbf{u}_g < 0\); (iv) gas temperature reaches the floor of the cooling function or the cooling time becomes shorter than the dynamical time \(t_{\text{dyn}} = \sqrt{3\pi/(32G\rho_{\text{b}})}\). When these conditions are satisfied, a stellar population particle is formed at a random position in the cell, with the same velocity as the gas, and mass that increases at a rate of \(m = m_{\star}(\Delta t/\tau_{\star}) \exp(-\Delta t/\tau_{\star})\), where \(\Delta t\) is the time since formation of the particle, \(\tau_{\star} = \max(t_{\text{dyn}}, 10\text{ Myr})\), and \(m_{\star}\) is the final mass of the particle. The final mass is \(m_{\star} = \epsilon_{\text{SF}} dt / t_{\text{dyn}} p dx\), where \(\epsilon_{\text{SF}} = 0.05\) is the star formation efficiency, \(dt\) is the timestep, and \(dx\) is the local cell size. There is a corresponding removal of gas mass from the surrounding cell during this process.
Table 1. Model parameters

| Parameter                  | Value |
|----------------------------|-------|
| $M_{\text{SN}}$            | $10^{12}$ $M_\odot$ |
| $c$                        | 12    |
| $\rho_{\text{core}}$       | $5.24 \times 10^{-24}$ g cm$^{-3}$ |
| $D$                        | 0.325 kpc |
| $\Sigma$                   | $100 M_\odot$ pc$^{-2}$ |
| $T_0$                      | $10^6$ K |
| $B_{\text{orb}}$           | $3 \mu G$ |
| Star Formation              |       |
| $n_{\text{min}}$           | 10 cm$^{-3}$ |
| $T_{\text{form}}$          | 300 K |
| $m_{\text{min}}$           | $10^5 M_\odot$ |
| $\epsilon_{\text{SF}}$     | 0.05  |
| Stellar Feedback            |       |
| $f_{\text{rel}}$           | 0.25  |
| $f_{\text{cr}}$            | 0.1   |
| $\epsilon_{\text{SN}}$     | $10^{51}$ erg/(M$_{\odot}$ c$^2$) |
| $M_{\text{SN}}$            | $100 M_\odot$ |

Notes. From top to bottom the rows contain: (1) halo mass; (2) concentration parameter; (3) initial midplane density; (4) initial scale height of the gas disk; (5) initial gas surface density; (6) initial temperature; (7) initial magnetic field strength; (8) gas density threshold for star formation; (9) floor temperature; (10) minimum stellar population particle mass; (11) star formation efficiency; (12) fraction of stellar mass returned to the ISM; (13) fraction of supernova energy bestowed unto CRs; (14) SN energy per rest mass energy of newly formed stars; (15) rest mass energy of newly formed stars per SN.

In order to keep the number of particles manageably small we set a minimum particle mass $m_{\text{min}} = 10^5 M_\odot$. We still permit particles with $m_\star < m_{\text{min}}$ to form; their masses are given by $m_\star = 0.8 \rho dx^3$ forming with a probability $m_\star/m_{\text{min}}$.

We include stellar feedback from winds and SN by adding gas mass at a rate $f_{\text{w}} \rho_{\text{core}} = f_{\text{w}} \rho_{\text{in}}$ into the cell surrounding a stellar population particle. The injected gas has a velocity equal to that of the source particle, thermal energy equal to $(1 - f_{\text{cr}})\epsilon_{\text{SN}} \rho_{\text{in}} c^2$, and CR energy equal to $f_{\text{cr}} \epsilon_{\text{SN}} \rho_{\text{in}} c^2$, where $f_{\text{cr}}$ is the fraction of total SN energy given to CRs. We assume $f_{\text{cr}} = 0.25$ for the fraction of returned mass from the star to the ISM and $\epsilon_{\text{SN}} = 10^{51}$ erg/(M$_{\odot}$ c$^2$) for the energy injected by one supernova per M$_{\odot}$ (Guedes et al. 2011; Hanasz et al. 2013) of mass of a newly formed stellar population particle, corresponding to a Kroupa (2001) initial mass function. The mass of the stellar population particle is reduced appropriately after the gas injection into the ISM. The parameter choices are summarized in Table 1.

2.4 Cosmic ray streaming

In the self-confinement model of CR transport through the ISM, CRs stream along magnetic field lines, exciting Alfvén waves due to the streaming instability, subsequently limiting the CR streaming speed to the Alfvén speed (Zweibel 2013).

As relativistic, charged particles (usually protons), CRs gyrate around a local magnetic field line at the frequency $\Omega_B/\gamma_{\text{rel}}$ and gyro-radius $r_g = \gamma_{\text{rel}} c/\Omega_B$, where $c$ is the speed of light. $\gamma_{\text{rel}}$ is the Lorentz factor, $\Omega_B = eB/|m_pc|$ is the non-relativistic cyclotron frequency, and $m_p$ and $e$ are the proton mass and charge, respectively. CRs strongly interact with Alfvén waves when the resonance condition $k \parallel = 1/(\mu_B g)$ is met; the Alfvén parallel wavevector $k \parallel$ (with respect to the local magnetic field) is of order the inverse of the CR gyroradius projected onto the plane of the wave by the cosine of the pitch angle $\mu$. At smaller gyro-radii, the local magnetic field does not change much over a CR orbit reducing the interaction, and at larger gyro-radii, the CR samples a large enough spatial region that the effects of the fluctuating field cancel out over the orbit.

Alfvén waves are amplified by resonant scattering of CRs at a rate shown by Kulsrud & Pearce (1969) and Wentzel (1974)

$$\Gamma_g = \frac{\pi}{3} \Omega_0 n_{\gamma_{\text{rel}}} \left( \frac{\gamma_{\text{rel}}}{n_{\gamma}} \right) \left( \frac{u_A}{u} - 1 \right),$$

where $n_{\gamma_{\text{rel}}} = n_{\gamma}$ is the number density of CRs with sufficiently large gyro-radii (directly dependent on $\gamma_{\text{rel}}$ and also the CR energy) to be resonant with the Alfvén wave, $n_{\gamma}$ is the ion number density, and $u_A$ is the Alfvén speed. CRs with larger gyro-radii can still be resonant as the projection of the orbit to the plane of the wave can meet the resonance condition. Amplification of Alfvén waves occurs until the CRs become isotropic in the wave frame and stream at $u_A$. In addition to growth, Alfvén waves experience damping by various mechanisms, in particular by ion-neutral friction, non-linear Landau damping, or turbulent damping. As a result of this damping, CR motion will be super-Alfvénic to a degree depending on the damping rate.

Given that the galactic astrophysical environment is magnetized, turbulent, and significantly ionized (McKee & Ostriker 2007; Sharma et al. 2009; Brandenburg & Lazarian 2013), we consider the effects of MHD turbulence stirred up by SN feedback. This was originally suggested by Yan & Lazarian (2002) and quantified in Farmer & Goldreich (2004) using the strong, incompressible MHD cascade (Goldreich & Sridhar 1995).

As Alfvén waves pass through turbulent eddies, they are irreversibly distorted. The turbulent eddies are anisotropic and aligned with the magnetic field (e.g., Higdon 1984). As a result of this anisotropy, the Alfvén waves that experience the least amount of distortion are those with wave vector parallel to the local magnetic field, which is exactly the case for the waves generated by the streaming instability.

The damping rates depend on the properties of turbulence that exists in the environment, which is characterized by the turbulent Alfvén Mach number $M_A = \frac{\sigma}{\gamma_{\text{rel}}}$, where $\sigma$ is the gas velocity dispersion, and the inertial range of the turbulence, depending on the ratio of the CR gyro-orbit to the injection length scale. Turbulence can be sub-Alfvénic, $M_A < 1$, and either strong or weak, depending on whether $r_g/L$ is greater or less than $M_A^3$ respectively. $L$ is the length scale at which turbulence is driven. Turbulence can also be super-Alfvénic, $M_A > 1$, and either strong or hydro-like, depending on whether $r_g/L$ is greater or less than $M_A^3$ respectively. Lazarian (2016) provides a general study of the Alfvén wave damping rates $\Gamma_g$ for each regime of turbulence. The results are summarized in Table 2.
As an example, we derive the CR streaming speed assuming (2017), we can parameterize the CR transport speed by balancing the turbulent wave growth and turbulent damping rates. As an example, we derive the CR streaming speed assuming the weak, sub-Alfvénic turbulent damping rate $\Gamma_d$, weak and compare it to the streaming instability growth rate

\[
\Gamma_E = \Gamma_d, \text{ weak}
\]

\[
\frac{1}{6} \Omega_b n_{\text{CR}}(> \gamma_{\text{rel}}) \left(\frac{u_s}{u_A} - 1\right) = \frac{M_A^{8/3}}{r_L^{2/3} L^{1/3}} \Gamma_d
\]

we then solve for the streaming speed $u_s$

\[
u_s = u_A \left(1 + \frac{u_A}{\Omega_b n_{\text{CR}}(> \gamma_{\text{rel}}) \frac{M_A^{8/3}}{r_L^{2/3} L^{1/3}}} \right)
\]

We set the length scale $L = 10$ pc (Iacobelli et al. 2013). A similar analysis using the damping rates appropriate for the other turbulence regimes yields the remaining three expressions for the streaming speed. In general, we write

\[
u_s = u_A f(n_i, n_{\text{CR}}, B, \sigma)
\]

where the proportionality $f$ is a function of ion and CR number densities, $n_i$ and $n_{\text{CR}}$, magnetic field strength $B$, and velocity dispersion $\sigma$.

The streaming speed boost above the Alfvén speed ($f - 1$) is listed in the last column in Table 2. The expressions for the boost show expected dependencies on the environment. The streaming boost is proportional to $n_i$ and $\sigma$ and inversely proportional to $B$ and $n_{\text{CR}}$. For higher ion density or velocity dispersion, all other parameters fixed, stronger turbulence can more efficiently damp Alfvén waves, leading to faster CR propagation. On the other hand, a higher magnetic field strength results in higher growth rate of Alfvén waves due to the streaming instability, trapping CRs more effectively and thus reducing their effective speed. Similarly, a greater density of CRs generates more Alfvén waves, also trapping CRs more effectively and slowing down CR propagation. In our simulations we use a constant velocity dispersion. The assumption of constant velocity dispersion is consistent with the decay of the turbulence strength from central star formation regions to the halo (Stone et al. 1998) as the turbulent Alfvén Mach number, $M_A$, still decreases with height above the midplane because the Alfvén speed increases. We compare results of simulations with two different gas velocity dispersion values $\sigma = 5$ km/s and 10 km/s, which are representative of turbulence in the disk, as the turbulent structure near the disk (where the wind is launched) will most likely dictate the resulting galactic wind structure and evolution (Kim & Ostriker 2018). Therefore, we do not expect the results to change significantly if instead of considering constant $\sigma$, we use a $\sigma$ profile declining with distance from the midplane. We choose constant $\sigma$ also because quantifying $\sigma$ on-the-fly in the simulation would pose additional challenges associated with averaging velocities over finite volumes.

CRs experience an effective drag force as they propagate down the pressure gradient $\nabla P_{\text{CR}}$ and scatter off MHD waves, leading to heating of gas. The heating term $|u_A \cdot \nabla P_{\text{CR}}|$ depends on the Alfvén speed $u_A$ and not the potentially super-Alfvénic streaming speed $u_s$ because the transfer of energy from CRs to the gas is only due to the portion of streaming caused by MHD waves (see the Appendix in Ruszkowski et al. 2017).

**2.5 Simulation setup**

We simulate a section of a galactic disk in an box of dimensions $2 \times 2 \times 40$ kpc$^3$, elongated in the direction $z$ above the mid-plane. Previous work has shown the importance of including sufficient height in these types of slab simulations in establishing a realistic temperature distribution in the halo (Hill et al. 2012). We choose the vertical extent of the box to be equal to 40 kpc. A box of such height is sufficiently extended to limit the above-mentioned problem, while not compromising feasibility of our computations.

We use periodic boundary conditions for the box sides perpendicular to the disk plane and diode boundary conditions for those parallel to the disk plane. The diode boundary conditions do not allow in-fall back into the box (e.g., Sur et al. 2016). We do not include the effects of differential rotation due to large scale galactic motion in order to simplify the simulation and focus on feedback processes. We use static mesh refinement that varies according to height $|z|$ above the mid-plane, achieving a maximum resolution of 31.25 pc in the disk for $|z| < 2$ kpc, and progressively coarser resolution of 62.5 pc for $2$ kpc $< |z| < 5$ kpc, and a minimum resolution of 125 pc elsewhere in the halo.

We initialize the simulation with the vertical equilibrium density solution for a stratified, isothermal self-
gravitating system (Spitzer 1942; Salem & Bryan 2014) as follows
\[
\rho(z) = \begin{cases} 
\rho_0 \text{sech}^2 \left( \frac{z}{Z_0} \right) & \rho(z) > \rho_{\text{halo}} \\
\rho_{\text{halo}} & \text{otherwise,}
\end{cases}
\]

where \(\rho_0\) is the initial mid-plane density and \(Z_0\) is the vertical scale height. We can define the initial disk surface gas density as \(\Sigma_0 = \int_{-20\text{kpc}}^{20\text{kpc}} \rho(z)dz\). \(\rho_{\text{halo}} \approx 1.0 \times 10^{-28} \text{g/cm}^3\) is the initial density of the halo. The parameters we chose for the gas distribution correspond to the average gas surface density within 10 kpc for a MW-type galaxy.

The magnetic field is initially oriented along a horizontal direction and its magnitude follows the density distribution such that \(B \propto \rho(z)^{2/3}\) with the mid-plane value \(B_0 = 3 \mu\text{G}\). We initialize the simulation with a constant temperature \(T = 10^4\) K.

3 RESULTS

We compare four simulations that differ in the value of the CR streaming speed \(u_{\text{cr}} = f u_A\). The first case is purely Alfvénic CR streaming with \(f = 1\), where there is no dissipation of Alfvén waves. The second and third cases correspond to locally-determined CR streaming following Eq. 12 using the appropriate turbulence regime for the environment. The local streaming simulations assume a constant velocity dispersion, \(\sigma = 5 \text{ km/s or } 10 \text{ km/s, in the turbulent damping formulae from Table 1}\). These values of velocity dispersion are on the order of the sound speed. The velocity dispersion could potentially be even higher. For example, Boettcher et al. (2016) find an upper limit of 25 km/s for turbulent velocity dispersion from optical emission-line spectroscopy in the edge-on galaxy NGC 891.

Since the wind is launched from a roughly one kpc tall region just above the dense and thin galactic disk, we first examine where this region in our simulations falls in the parameter space of the CR streaming speed. A discussion of the parameter space is important as we can only consider a limited number of simulations. Examining the parameter space allows us to develop intuition for the possible results of a simulation. Average values of the ionized ISM in our simulations are \(n_i \sim 10^4 \text{cm}^{-3}\), \(B \sim 0.5 \mu\text{G}\), and \(n_i \sim 10^{-4} \text{cm}^{-3}\). Figure 1 shows the parameter space for these typical values, where CR streaming is expected to be nearly Alfvénic with \(\log(f - 1) < 0.1\), and also shows the transition to significantly super-Alfvénic streaming. At a velocity dispersion \(\sigma = 10 \text{ km/s, the parameter space plot indicates that super-Alfvénic streaming is significant for the typical density of } n_i \sim 10^{-4} \text{cm}^{-3}\) in the launching region. Furthermore, since the typical ion density value we see is an average over all of the cells at a given height above the mid-plane, we can expect cells of even faster CR streaming compared to \(u_A\) from the slightly over-dense regions (see the slice plots in Figure 2 for a qualitative look at the variation in density). At a velocity dispersion of \(\sigma = 5 \text{ km/s, the typical gas density falls mostly in the region of Alfvénic streaming. However, the average density is large enough that slightly over-dense cells can still move into the super-Alfvénic regime, indicating that turbulent damping will still influence the global wind.}

**Figure 1.** The parameter space for the CR streaming speed boost \(f - 1\) factor for fixed magnetic field strength \(B\) and CR density \(n_i\), and varying ion density \(n_i\) and velocity dispersion \(\sigma\). The damping formulae in Table 2 are used. Below a value of \(\log(f - 1) = -1\), shown in yellow, there is no significant super-Alfvénic CR streaming and turbulent damping is ineffective. The black line indicates the boundary \(M_A = 1.0\) and the red line indicates the transition from weak to strong, sub-Alfvénic turbulence. The parameters we use for the plot correspond to approximate values of quantities within the kpc size ionized ISM, above the thin galactic disk.

Further comparisons we discuss here are between the Alfvénic and stronger turbulence \((\sigma = 10 \text{ km/s})\) cases, as the weaker strength turbulence results follow similar trends to that of the stronger turbulence. Figure 2 shows a qualitative comparison between the Alfvénic streaming and streaming with turbulent damping simulations in ion and CR density slices at a snapshot of 200 Myr, when the wind settles down. Figure 3 shows the volume-weighted profiles of ion and CR density versus height above the midplane for the Alfvénic case, as well as the profiles for streaming with tur-
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Figure 2. Ion and CR number density slice of dimensions ±5 kpc along z direction perpendicular to the midplane, for two simulations at 200 Myr: Alfvénic streaming and streaming including turbulent damping (σ = 10 km/s). The Alfvénic simulation results are on the left hand side of each pair of plots, and the turbulent damping simulations are on the right side of each pair. The gas distribution (left pair) is slightly more extended in the turbulent damping simulation than for the Alfvénic streaming simulation. Similarly, the CR distribution (right pair) is significantly more extended in the turbulent damping simulation.

Bululent damping relative to the Alfvénic one. These profiles are volume-weighted to provide a fair comparison between the slice images and the averaged ion and CR densities. At 200 Myr there is a systematically more extended ion and CR distribution in the local turbulent damping case compared to the Alfvénic case. The slices show that the ion density is higher in the mid-plane for local streaming. There is also a noticeable increase in the ion density farther away from the mid-plane at the top of the figure (|z| = 5 kpc). The far right column of Figure 3 quantifies these observations with relative profiles of ion and CR density. Within 5 kpc of the mid-plane, the average number density of both ions and CRs is about twice as large at a given height. Additionally, at the mid-plane the CR number density profile approaches that of the Alfvénic streaming simulation. These results are due to the enhanced CR streaming near the mid-plane. With a boost in streaming, there is enhanced feedback—CRs can more effectively leave the dense mid-plane, allowing interaction with more tenuous gas and providing less pressure support against self-gravity of the midplane gas. This leads to an increased SFR.

The boost in streaming speed is seen in the mass-weighted profile of CR streaming speed shown in Figure 4, where the stronger turbulence case is shown in blue. The profile is mass-weighted because we are interested in the influence that CRs have in accelerating gas. Near the mid-plane the boost factor f is large and remains above f = 2 within the thin galactic disk (|z| < 500 pc), and weakly super-Alfvénic at larger heights as turbulent damping becomes ineffective.

Since we do not track the CR spectrum or include energy dependent processes in our simulations, we cannot make predictions about observational signatures (e.g., synchrotron emission) produced by CRs. Generally, a CR distribution more extended in height above the mid-plane does result in stronger radio emission in the halo around a galaxy (Wiegert et al. 2015). CR feedback could also influence the radio luminosity through its affect on the SFR (e.g. Li et al.)
The trends for the weaker turbulence strength follow those described for stronger turbulence, although, as expected, they are closer to the Alfvénic streaming results, due to the corresponding reduction in the strength of turbulence. Halving the velocity dispersion produces a significant reduction in streaming speed. For example, $f^{-1} \propto \sigma^2$ for strong, sub-Alfvénic turbulence, so halving $\sigma$ will reduce average streaming by a factor of four. Figure 4 shows that both cases have high CR average streaming near the mid-plane and weakly super-Alfvénic streaming at larger heights, with the weaker turbulence run having a systematically smaller $f$ values.

The transition from the limiting case, Alfvénic streaming, with no turbulent damping, to progressively stronger turbulence is seen in the wind properties in Figure 5, which shows comparisons for the SFR, mass outflow, and mass loading of all four simulations. The mass flux and integrated mass flux are calculated across two different surfaces (2.5 and 5.0 kpc) above the mid-plane. The SFR plots include the result of a simulation without CRs. This case can also be thought of as the limiting case for maximal CR transport or equivalently no confinement of CRs.

For times up to 50 Myr, the simulations appear similar as there has not been significant and sustained CR production. After 70 Myr, there are enough CRs to influence feedback and the SFR profiles diverge. In the simulation without CRs, gas cools and collapses more easily to form stars due to the absence of CR pressure. For our specific implementation, this stellar feedback fails to launch a significant wind. The result is a comparatively greater SFR than in the other simulations with CRs.

In the case where there are CRs, but no streaming (i.e., $f = 0$) or diffusion, CRs are transported by advection. CRs cannot escape the mid-plane effectively, halting further cold gas collapse through additional pressure support that is not radiated away. The first column of Figure 5 shows the SFR and wind properties for a simulation with only CR advection. There is a weak galactic wind, low SFR, and puffed-up disk morphology. These results agree with other works (see Salem & Bryan 2014; Girichidis et al. 2016; Simpson et al. 2016; Ruszkowski et al. 2017; Farber et al. 2018).

When CR transport is added, CRs can escape the dense disk, influencing the evolution of the simulation. Ruszkowski et al. (2017) included comparisons between no CR transport ($f = 0$) and Alfvénic CR transport ($f = 1$), finding an increased SFR and stronger wind in the Alfvénic streaming case. They find the same trend of an increasing and more
sustained SFR with progressively faster CR streaming, up to $f = 8$ or $8$ times the Alfvén speed. Our simulations agree with this trend as the SFR increases for stronger turbulence, which leads to faster CR transport in our simulations. Our simulations extend their treatment of CR physics by allowing for spatial and temporal variations in the CR transport speed. The higher streaming speed in the ISM allows CRs to escape the dense mid-plane, allowing for further gas collapse. Indeed, as the velocity dispersion increases, the SFR increases and approaches the peak SFR of a simulation without CRs. The differences in time evolution of the outward mass flux (bottom row, plotted alongside the SFR in Figure 5) for increasing CR transport are weaker. The peak mass flux is similar for all three simulations with CR transport; however, the evolution of the mass flux does increase when turbulent damping is included in CR transport.

In the Alfvénic transport simulation, CRs all have the same streaming speed as they leave the galactic plane. With turbulent damping included, CRs leave the galactic plane quicker and interact with the lower density gas above, which is easier to accelerate, so there is higher mass flux at earlier times. At about 75 Myr, the mass flux for Alfvénic case is low, while the mass flux is already significant for the turbulent damping simulations.

The increase in the SFR has a significant impact on instantaneous mass loading (ratio of the outward mass flux $\dot{m}_w$ to the SFR), seen in the top row of Figure 5. We find that the instantaneous mass loading is almost an order of magnitude smaller for the stronger turbulence simulation compared to Alfvénic streaming. This is because for stronger turbulence, CR transport is faster and the SFR is larger. This fact, combined with weaker sensitivity of the mass flux to CR transport speed, makes the instantaneous mass loading a decreasing function of the velocity dispersion. We plot the mass loading through two surfaces 2.5 kpc and 5 kpc above the mid-plane, finding similar trends. For the Alfvénic CR streaming simulation, the mass loading peaks at a value of about 40, while for the stronger turbulence simulation, it peaks at about 5. These values are consistent with observational constraints, which constrain instantaneous mass loading in range $10^{-2}$ and $10^1$ (Bland-Hawthorn et al. 2007). For example, Heckman et al. (2015) uses ultraviolet absorption lines to investigate the properties of galactic winds of a collection of low redshift starburst galaxies finding instantaneous mass loading factor values up to 1 to 4. Additionally, Strickland & Heckman (2009) find a constraint of mass loading factors up to 2.8 for the starburst galaxy M82. In our simulations, we assumed a MW-like halo, which is more massive than the galaxies studied above. However, we expect that the feedback effects would be stronger for lower mass halos, and should follow trends similar to those we described above. Mass loading values exceeding 10, as we find in the Alfvénic CR streaming case, can be suppressed by the presence of turbulence, landing within the observational constraints, as shown in the mass loading of the stronger turbulence simulation.

On the other hand, we find that the integrated mass loading (ratio of the total wind mass $M_w = \int_0^{200}\dot{m}_w dt$ to the stellar mass $M_*$), is almost insensitive to the parameters we considered. The values we find for the integrated mass loading are about 0.2-0.3, roughly consistent with values from isolated slab simulations (e.g., Farber et al. 2018) and also global simulations (e.g., Ruszkowski et al. 2017). While Ruszkowski et al. (2017) found that the integrated mass loading increased with faster CR streaming, their simulations were global.

### 3.1 Other relevant physical processes

Our simulations do not account for various aspects of CR transport and CR interaction with the gas.

(i) We do not include additional Alfvén wave damping processes such as ion-neutral damping and non-linear Landau damping. As ion-neutral damping is important when the medium that the CRs pass through is not completely ionized. The effects of ion-neutral damping on the galactic wind have been studied recently by Farber et al. (2018). Non-linear Landau damping occurs due to wave-particle interactions (Kulsrud 2005). It is expected that this damping will not be dominant in astrophysical settings because it is self-regulating (see Lazarian 2016).

(ii) Our implementation of turbulent damping of Alfvén waves from Lazarian (2016), while still dependent on the local properties of the ISM and halo, is not completely self-consistent. First, we assumed a constant gas velocity dispersion in the turbulent damping rates, which strictly speaking is not true as turbulence will decay farther away from the star forming regions. However, this assumption is sufficient in our case because the properties of the launching region (close to the mid-plane) should determine the properties of the overall wind. Despite this assumption, the turbulent Alfvén Mach number (velocity dispersion divided by the Alfvén speed) nevertheless decays with height above the mid-plane as expected because the Alfvén speed increases with height. The streaming speed profile in Figure 4 also decays with height as expected, approaching Alfvénic streaming in the halo. However, the assumption of constant velocity dispersion does not allow us to study in detail the different regimes of turbulence presented in Lazarian (2016), as the halo turbulence strength (i.e. away from the wind launching...
zone) will be significantly overestimated. Second, we do not account for the level of ionization in the ISM and halo gas in determining the CR streaming speed. Only the ionized gas will participate in the growth and damping of Alfvén waves. However, since the ISM and halo are significantly ionized, especially in the wind launching region just above the dense mid-plane, we did not specifically estimate the level of ionization in the gas and assume that the gas is fully ionized.

(iii) We also do not account for energy-dependent processes. The CR streaming speed boost $f - 1$ increases with energy (or $\gamma_{\text{rel}}$), so higher energy CRs will escape faster. In a simple picture, we might expect that the CR spectrum will steepen from the initial spectrum. Furthermore, we do not account for loss of energy by CRs, due to hadronic losses as well as Coulomb losses, where CRs interact inelastically with atoms in the ISM.

(iv) There are also additional feedback mechanisms we did not implement. One example is the mechanism based on the radiation pressure from massive stars onto ISM dust in driving a galactic wind (Hopkins et al. 2012; Zhang & Thompson 2012). Including this mechanism involves calculating the radiation field using radiative transfer models, and including components of the ISM that interact with the field, such as dust, and is beyond the scope of this paper.

(v) Finally, CR propagation depends on the details of the MHD turbulent cascade. In our model, we assume that turbulence only interacts with the CR-generated Alfvén waves and not the CRs themselves. In the extrinsic turbulence picture, turbulence scatters CRs as they propagate through the ISM with fast modes identified as the major agent of CR scattering (Yan & Lazarian 2002). A realistic magnetic topology is also important since CRs gyrate and follow the magnetic field and can also diffuse across field lines, potentially even super-diffusively (i.e., Lazarian & Yan 2014). However, we expect the galactic winds to be mostly sub-Alfvénic with the magnetic field not being strongly tangled, so the Alfvénic perturbations will not scatter CRs efficiently (Yan & Lazarian 2002, 2004, 2008). Overall, all of these processes interact in a non-linear fashion over a large range of scales, so a more complete description of CR transport in a galaxy remains to be fully understood.
4 CONCLUSIONS

We perform three-dimensional magnetohydrodynamical simulations of a section of a galactic disk considering the impact of locally-determined cosmic ray (CR) transport on the properties of galactic winds. CR transport is treated within the self-confinement model, where the balance between wave growth and its decay by turbulent damping of self-excited Alfvén waves determines the bulk CR streaming speed relative to the gas. We employ the model of the streaming instability damping in Lazarian (2016) and find that the coupling of CRs experience significant spatial variations. Due to turbulent damping, the CRs are weakly coupled within the regions of the interstellar medium with higher level of sub-Alfvénic turbulence. We compared simulations with and without turbulent damping of the CR streaming instability. Our conclusions are as follows:

(i) We find that the star formation rate (SFR) increases when turbulent damping is included in the CR transport model and continues to increase with the strength of turbulence. Stronger turbulence damps confining Alfvén waves and leads to a corresponding boost in the average CR streaming speed. As the CRs can leave the dense mid-plane more easily, the reduced pressure support from CRs allows gas to collapse and form stars more effectively.

(ii) We show that the cumulative mass loading factor, the ratio of integrated wind mass to cumulative stellar mass, is insensitive to the impact of turbulent damping on the CR streaming speed. For both strengths of turbulence tested, the cumulative mass loading factor asymptotes to the same value as the Alfvénic streaming run.

(iii) We show that the instantaneous mass loading is very sensitive to increased CR streaming speed due to turbulent damping.

(iv) We demonstrate that the increased CR streaming speed due to turbulence results in more extended gas and CR density distributions. The larger SFR results in more stellar feedback, directly increasing the number of CRs produced in the mid-plane. These CRs escape the dense mid-plane more quickly with an increased streaming speed, widening the CR distribution in height. Escaping the central regions allows CRs to interact with lower density gas, which is easier to accelerate into the galactic wind, widening the gas distribution in height.

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