The Ultimate Fate of Cosmic Rays from Galaxies and their Role in the Intergalactic Medium

Brian C. Lacki
Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA, brianlacki@ias.edu

ABSTRACT
The majority of cosmic rays (CRs) generated by star-forming galaxies escape them and enter the intergalactic medium (IGM). Galactic wind termination shocks might also accelerate CRs. I show that the mean pressure of these CRs can reach to within an order of magnitude of the mean Lyman-α forest thermal pressure. At \( z > 1 \), their pressure may have even been dominant. I also demonstrate that, whichever IGM phase the CRs reside in, they contribute significantly to its pressure if its temperature is \( \sim 10^4 \) K, as long as pionic and Coulomb losses are negligible. Where CRs end up depends on the structure and strength of intergalactic magnetic fields. I argue that CRs end up at least 30 kpc from their progenitor galaxies. CRs may self-confine in the IGM to the sound speed, generating \( \gtrsim 10^{-13} \) G magnetic fields. These considerations imply the existence and importance of a nonthermal IGM.

Keywords: intergalactic medium — cosmic rays — galaxies: haloes

1 INTRODUCTION
Most of the baryonic matter in the Universe is not in stars or galaxies, but in the gas between the galaxies, the intergalactic medium (IGM). Far from being a uniform background gas, the IGM has a rich structure with several phases spanning a wide range of physical conditions. The scaled densities \( \delta \equiv \rho/(\rho_\text{crit}) \) within the IGM vary by orders of magnitude. At present, about one-third of the baryonic mass is in the Lyman-α (Lyα) forest, a volume-filling \( 1 \, \text{K} \) photonization phase with \( \delta \lesssim 10 \) (Bi & Davidsen 1997). Before \( z \approx 1 \), this phase contained most of the baryonic mass of the Universe (Davé et al. 1999). As some of this gas collapses into smaller structures, it is shock heated to form the Warm Hot Intergalactic Medium (WHIM), a moderately dense \( \delta \sim 10 - 100 \), \( 10^5 - 10^7 \) K phase that presently contains \( \sim 1/2 \) of the baryonic mass (Cen & Ostriker 1999). Finally, some of the material has collapsed even further into ‘condensed’ structures: these include the galaxies themselves, their multiphase gaseous haloes, and hot intracluster media. The circumgalactic gas results from the interaction of galaxies and the IGM, through accretion on to galaxies and expulsion by winds, and is itself complex, with cool dense and warm rarefied phases (e.g., Chen, Lanzetta, & Webb 2001).

But is this picture of the IGM complete — an interplay of thermal gas, galaxies, and gravity? Just as in galaxies, the thermal gas may be complemented by pervasive nonthermal fields: the cosmic rays (CRs) and magnetic fields. Detections of radio synchrotron emission within galaxy clusters prove that both CRs and magnetic fields exist there, and much work centres on how they are generated and interact with the intracluster gas (e.g., Subramanian, Shukurov, & Haugen 2003; Ferrari et al. 2008). Radio emission is also detected from galaxy filaments, suggesting similar processes at play (Brown & Rudnick 2004; see also Ryu et al. 2008).

Evidence for nonthermal processes in the rest of the IGM is scant, but there are theoretical reasons to expect they exist. A nonthermal IGM can take the form of CRs accelerated by structure formation shocks (Loeb & Waxman 2000; Keshe, Waxman, & Loeb 2004), injected by dark matter annihilation throughout the Universe (Mapelli, Ferrara, & Perpaoli 2006), or escaping from active galactic nuclei jets (Vecchio et al. 2013); pervasive intergalactic magnetic fields (IGMFs) seeded by early galaxies, plasma processes in the IGM, or even primordially in the Big Bang (Widrow 2002; Schlickeiser 2012; Yoon, Schlickeiser, & Kolberg 2014); and low frequency nonthermal radio waves that heat the IGM when absorbed (Lacki 2010). Whether electromagnetic TeV γ-ray cascades heat the IGM nonthermally through plasma instabilities (Broderick, Chang, & Pfrommer 2012; Chang, Broderick, & Pfrommer 2012) is the topic of intense recent debate (Schlickeiser et al. 2012; Miniati & Elviv 2013), although recent simulations suggest this mechanism is fairly ineffective (Sironi & Giannios 2014).

A guaranteed source of nonthermal energy in the IGM is
the CRs accelerated by star-forming galaxies (SFGs). Most of the CR energy is in GeV protons. They diffuse out of SFGs, losing only a few percent of their energy through pion production and ionization in Milky Way-like galaxies (Strong et al. 2010, hereafter S10). Starbursts and high-z normal galaxies have more gas, and likely heavier losses. Yet, γ-ray observations of the starbursts M82 and NGC 253 indicate that ∼ 20 – 40% of their CR power is lost to pion production, with the majority (∼ 60 – 80%) escaping, most likely in a starburst wind (Lacki et al. 2011; Abramowski et al. 2012; Ackermann et al. 2012). The termination shocks of these winds may also accelerate CRs (Jokipii & Morfill 1985, 1987). Thus, a large reservoir of CRs builds up in the IGM over the history of cosmic star formation.

This population has been largely ignored. Nath & Biermann (1993) and Samui, Subramanian, & Srivastava (2005) studied how CRs from SFGs could have reionized the IGM, or heated it at high redshift. But the pionic energy loss time for CRs with kinetic energies > GeV is ∼ 200  δ−1 yr, so energy injection is negligible in the rarefied IGM (Mannheim & Schlickeiser 1994; Schlickeiser 2002, hereafter S02). Miniati & Bell (2011) proposed that CRs from the first SFGs seeded the IGMF. A few other estimates of the intergalactic CR spectrum, with widely disparate assumptions, are briefly given in Dar & de Rujula (2003) and Lipari (2005).

CRs can nevertheless couple dynamically to the IGM and its weak magnetic fields. I show here that the mean intergalactic energy density of CRs from SFGs is plausibly within a factor of a few of the Lyα forest pressure (Section 2). I also show that CRs are likely to reach the IGM (Section 3). I assume ΩΛ = 0.75, Ωm = 0.25, H0 = 70 km s−1 Mpc−1 for the cosmology. For the baryonic density, I use Ωb = 0.045, a hydrogen mass fraction XH = 0.75, a helium mass fraction XHe = 0.25, and mean molecular weight μ = 0.6 (complete ionization) for a mean IGM comoving number density of ⟨nIGM⟩ = 4.1 × 10−7 cm−3. All given densities are comoving unless otherwise stated.

2 THE PRESSURE OF INTERGALACTIC COSMIC RAYS

CR nuclei experience mainly adiabatic losses once they leave a galaxy. CRs in the IGM lose momentum as the Universe expands, CRs in a galactic wind lose momentum adiabatically as the wind expands, sacrificing their energy to the expansion. CRs in a galactic wind lose momentum adiabatically as the wind expands, sacrificing their energy to the expansion. CRs in the IGM lose momentum as the Universe expands. SFGs without SN-launched winds may still have more rarefied winds originating from their haloes and powered by CRs, as their streaming excites plasma waves that push halo plasma out (Breitschwerdt, McKenzie, & Völk 1999, hereafter B91). The existence of this kind of CR-driven halo wind is unproven – CRs may even simply diffuse out without energy losses (as assumed in GALPROP models; S10).

The equation for the comoving IGM particle momentum spectrum at redshift z is

\[
\frac{dN}{d\ln p} (p, z) = \int_\infty^p \frac{d^2 Q}{d\ln p \, dt} (p_{ini}, z_{ini}) \frac{d\ln p_{ini}}{dp} \frac{dt}{dz_{ini}} d\ln z_{ini},
\]

(1)

Particles are accelerated to momenta pini at a rate d^2Q/dlnp dt at redshift zini. I relate pini to p = ϵadv pini (1+z)/(1+zini), where ϵadv accounts for adiabatic losses within a galactic wind. For purely adiabatic losses, dlnpini/dlnp = 1. I consider Coulomb and pion losses later, as they are negligible if δ − 1.

The injection spectrum is modelled as a power law in momentum (d^2Q/dlnp dt = C p^γ), with spectral index Γ = 2.2. The normalization of the spectrum is set by a volumetric energy injection rate:

\[
\dot{E}_{\text{CR}} = \int_{E_{\text{GeV}}}^{E_{\text{TeV}}} \frac{p}{C} K_p^\gamma dE_{\text{p}},
\]

(2)

where K is kinetic energy. I calculate \dot{E}_{\text{CR}} by scaling to the comoving cosmic star-formation rate density ρSFR (Hopkins & Beacom 2006). Star formation creates young, massive stars that accelerate CRs in their winds or SNe. The star-formation rate is directly related to the SN rate as ΓSN = 0.0084 yr−1 [SFR/(M⊙ yr−1)] for the “Salpeter A” initial mass function used by Hopkins & Beacom (2006). Multiwavelength models of SFGs indicate that each SN accelerates ∼ 10^{25} erg of CRs (that is, 10^{45} s^{-1} of the 10^{51} erg released in mechanical energy; de Cea del Pozo et al. 2004; S10; Lacki et al. 2011; Yoast-Hull et al. 2013). CRs may also be accelerated by galactic wind termination shocks, where the winds are powered by SNe and contain some fraction ϵSN of the original SN mechanical energy. So I have

\[
\dot{E}_{\text{CR}} = 0.018 \text{ meV Gyr}^{-1} \text{ cm}^{-3} \left( \frac{\rho_{\text{SFR}} \times \rho_{\text{SN}}}{1 \text{ M⊙ yr}^{-1} \text{ Mpc}^{-3}} \right),
\]

(3)

Relativistic CRs advected out from their host galaxy in a wind of density ρ lose momentum as ρ^{−3/2}, so the ϵadv factor is simply the cube root of the ratio of the final and initial wind density. For example, a hypothetical B91 wind from the Milky Way initially occupies the disc with radius 10 kpc and the CRs move with an Alfvén speed of 10 km s−1. If the wind outflows spherically and reaches 1 Mpc with a speed of 300 km s−1 (B91), then ϵadv ∼ (4π(1 Mpc)^2(300 km s−1)) / (2π(10 kpc)^2(10 km s−1))^3/2 ∼ 0.012. Adiabatic cooling is much greater within winds from compact starburst regions, because the density contrast from the starburst to the IGM is huge.

The adiabatic energy scaling of CRs ranges from ρ^{2/3} for non-relativistic (≤ GeV) CRs to ρ^{−3/4} for relativistic CRs (≥ GeV). CRs with initial Lorentz factors ≲ ϵadv (1+z) are thus severely affected by adiabatic losses and do not contribute much to the IGM CR energy density. Yet since the injection spectrum is close to ρ^{−2}, much of the original energy is in very high energy CRs that always are relativistic.

3 The momentum scaling is due to the isotropic nature of these processes. Phase space volume is conserved, so as the real space volume goes as ρ^{−1}, the momentum space volume scales with ρ, and the momentum in one direction scales as ρ^{1/3}.
Cosmic Rays in Intergalactic Medium

Figure 1. Predicted comoving mean cosmic CR energy density. The dashed lines are for CRs accelerated at wind termination shock, while solid lines represent the original escaping population of CRs after experiencing adiabatic losses. Grey dotted lines show models including Coulomb and pionic losses with $\delta = 1000, 10^4, 10^5$ for wind termination shocks (upper three lines) or adiabatically cooled CRs ($\epsilon_{\text{adv}} = 0.01$; lower three lines). The grey shaded band is the expected mean IGM thermal pressure for $T_\text{cr} = 10^4 K - 10^6 K$. All plotted models assume that $n_0.1 = 1$.

For a $p^{-2.2}$ injection spectrum, the fraction of kinetic energy in always-relativistic CRs is roughly $\epsilon_{\text{adv}}^{-1}(1+z)^{-0.2}$, this cutoff factor is 0.4$(1+z)^{-0.2}$ for $\epsilon_{\text{adv}} = 0.01$. Even for a $p^{-2.4}$ spectrum, the cutoff factor 0.16$(1+z)^{-0.2}$ is $\sim 0.1$. Hence, the increased losses of non-relativistic CRs only have a moderate effect on the final CR energy density.

Although a wind could drain most of its CR energy by the time it reaches the IGM, the wind itself eventually stops at a termination shock when its ram pressure equals the surrounding IGM’s pressure. The termination shock itself may accelerate CRs, converting $\gtrsim 10\% (n_i \gtrsim 1)$ of the wind’s kinetic energy back into CRs and releasing them into the IGM (Jokipii & Morris 1985). However, the efficiency of CR acceleration in collisionless shocks depends on the conditions within the shock (e.g., Caprioli & Spokovsky 2014). These conditions are especially unknown in galactic wind shocks, as is whether CR acceleration actually takes place there. The B91 wind’s kinetic energy is powered by the CRs initially present in the galaxy, which themselves contain only 10% of the original SN power so that $\epsilon_{\text{SN}} = 0.1$. Powerful starburst winds may carry most of the SN mechanical power, implying $\epsilon_{\text{SN}} = 1$. Reacceleration can also occur at shocks within inhomogeneous winds (Dorie & Breitschwerdt 2012).

I find that with $\epsilon_{\text{adv}} = 1$, the comoving CR energy density $(U_{\text{CR}})/K_B = 0.02$ K cm$^{-3}$ at present, and it peaked at $z = 1.0$ at 0.1 K cm$^{-3}$ (Figure 1). About half of the present energy density is in CRs accelerated at $z < 0.4$ (in the past 4 Gyr). For termination shocks CRs with $\epsilon_{\text{SN}} = 0.1$, $(U_{\text{CR}})/K_B$ is ten times smaller. For comparison, the expected comoving thermal IGM energy density is 0.0075$T_z$ K cm$^{-3}$ for $T = 10^4 T_z K$ (grey band in Figure 1). We see that, if $\epsilon_{\text{adv}} = 1$, intergalactic CRs have an energy density greater than that of the Ly$\alpha$ forest. For $\epsilon_{\text{adv}} = 0.1$, CRs and Ly$\alpha$ forest thermal energy are in equipartition at $z \approx 1$.

Pionic and Coulomb losses matter on cosmological time-scales for GeV CRs if $\delta \gtrsim 1000$. Galactic winds remain fairly dense even $\sim 100$ kpc from their launch sites, with $\delta \gtrsim 1000$ in cool gas at $z \approx 0$ (e.g., Narayanan et al. 2008; Werk et al. 2014). Thus, I add these losses and consider cases when $\delta = 1000, 10^4$, and $10^5$. I integrate all momentum losses over redshift to relate $p$ and $\rho_{\text{esc}}$. I assume that all CRs are protons. The Coulomb loss rate is $\dot{p}_C = 3.1 \times 10^{-7} \delta (n_e) (1+z)^3 \beta_{\text{CR}} (\text{eV} \text{ c}^{-1} \text{ sec}^{-1})$ and the pionic loss rate is $\rho_{\text{esc}} = \rho_0 (n_e) (1+z)^3/(50 \text{ Myr})$ for $p \gtrsim 0.78 \text{ GeV} / c$ (Mannheim & Schlickeiser 1994; S02).

The grey dotted lines in Figure 1 represent the volume-mean CR energy density, if CRs are trapped in high-$\delta$ regions. With $\delta = 10^5$, the CR energy density is reduced by a factor 70 (6) at $z = 5 (0)$, whereas the reduction is only 1.7 (1.2) if $\delta = 1000$.

2.1 CR importance in overdense IGM phases

CRs might not actually fill the entire volume of the Universe, but instead may be confined to one IGM phase. Although these phases could be very overdense, the CR energy density is likewise greater since the same CR power is then being squeezed into a smaller confinement volume.

What is the ratio of CR energy density to thermal energy density in the phase the CRs end up in? If a fraction $f_\text{CR}$ of the CR energy occupies an IGM phase $i$, and if $i$ has a cosmic filling factor $\Phi_i$, then the CR energy density within $i$ is $U_{\text{CR}} = f_\text{CR} \phi_i \langle U_{\text{IGM}} \rangle$. The gas density in $i$ is limited by mass conservation to $n_i = (\Omega_i/\Omega_b) \phi_i \langle n_{\text{IGM}} \rangle$, where $\Omega_i$ is the baryonic mass fraction in $i$. The thermal energy density within that phase is $U_{\text{IGM}} = (3/2) n_i k_B T_i$, giving

$$\frac{U_{\text{CR}}}{U_{\text{IGM}}} = f_\text{CR} \frac{\phi_i}{\Omega_i} \frac{2 \langle U_{\text{IGM}} \rangle}{n_i k_B T_i},$$

The filling factors cancel out: if CRs end up mostly in one phase of the IGM, then all that matters are its mass fraction and its temperature (neglecting Coulomb and pionic losses). $U_{\text{CR}}$ exceeds the thermal energy density as long as $T_i < (2/3) f_i (\Omega_i/\Omega_b) \langle U_{\text{IGM}} \rangle / (n_i k_B T_i)$ and $\delta \lesssim 1000$.

At $z = 0$, the CRs dominate the energy density of their final IGM phase if $T_i < 3.6 \times 10^4 K (\Omega_i/\Omega_b) f_i \Phi$, where $\Phi \approx 0.1 - 1$ is the ratio of the actual ($U_{\text{CR}}$) and its value for $\epsilon_{\text{adv}} = 1$, $\epsilon_{\text{SN}} = 1$, and $\delta \ll 1000$. About half of the $z = 0$ IGM mass has a temperature $\sim 10^4 K$, including the Ly$\alpha$ forest and condensed haloes, indicating a major CR contribution to their pressure is possible. However, half of the IGM mass is WHIM with $10^5 - 10^7 K$ temperatures; if the CRs end up in WHIM, their pressure is insignificant.

At higher redshifts, CRs are even more important because $\rho_{\text{CR}}$ was much greater. Furthermore, most of the gas was in the uncollapsed $10^4 K$ Ly$\alpha$ forest. I find that CRs dominate the pressure of their host phase at $z = 1$ if $T_i < 1.6 \times 10^5 K (\Omega_i/\Omega_b) f_i \Phi$, a condition that applied to most of the IGM’s mass.

$4 \beta_{\text{CR}} = p/(K + m_c^2)$ is the CR speed in units of $c$. 

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2.2 Do CRs couple to the IGM?

In order for the CR pressure to affect the dynamics of the IGM, the CRs must interact with it. This happens whenever the CRs’ paths bend. When the IGM exerts a magnetic force on the CRs, the CRs exert a force back on the IGM.

The trajectories of CRs may bend for several reasons. CRs gyrate around field lines if there is a coherent magnetic field, but this acceleration has a time average of zero. CRs can self-confine and scatter off plasma waves in the IGM, diffusing parallel or perpendicular to magnetic field lines.

Yet even without these waves, CRs move along magnetic field lines. If the lines bend, then the CRs’ paths also bend, and the CRs exert a force on the IGM. CRs are deflected within some region of light-crossing time if the IGMF has coherence length $\lambda_B$ smaller than the region but larger than $\tau_L \equiv pc/(eB)$. The required magnetic field strength is then $B \gtrsim p/\langle et\rangle = 4 \times 10^{-22}$ G $p_{\text{GeV}}^{-1}$, where $t_{10} \equiv t/(10$ Gyr) and $p = p_{\text{GeV}}$ GeV/c.

If $\lambda_B$ is smaller than $\tau_L$ and $e$, the CRs can still be deflected after passing through many IGMF domains. Each domain exerts an impulse $dp = eB d\langle e\rangle$, where $dp \ll p$. A CR’s trajectory bends only when the sum of all the impulses is $\gtrsim p$. This condition is met when $B > pc/(e\sqrt{\lambda_B}) = 2 \times 10^{-29}$ G $p_{\text{GeV}}^{-1} \sqrt{\tau_{10}/(\lambda_B/\text{Mpc})}$. Several plausible mechanisms exist for generating coherent IGMFs this strong (e.g., Widrow 2002; Miniati & Bell 2011), and blazar $\gamma$-ray spectra indicate their presence (Dermer et al. 2011).

Thus, CRs are likely to provide significant pressure support in some IGM phase at $z \gtrsim 1$. If the CR pressure is not already exerted, then it cannot exert net forces. CRs that are trapped in collapsing IGM regions, though, are adiabatically heated, leading to pressure gradients. This may alter the equation of state of the IGM, for example, but the effects of the CRs remain unexplored.

3 WHERE ARE THE COSMIC RAYS?

3.1 Do CRs really even escape their galaxies?

Observations of quasar absorption lines indicate that winds from high-$z$ SFGs transport material out to $\gtrsim 100$ kpc (Heckman et al. 1999). Theory likewise suggests that even Milky Way-like galaxies host CR-driven winds in their haloes (B91). Ultimately, a wind with asymptotic speed $v_\infty$ and kinetic luminosity $E_\infty$ should flow out to the termination shock radius

$$R_s = \sqrt{E_\infty/(4\pi v_\infty^2 P_{\text{IGM}})} \approx 1.1 \text{ Mpc} \left[\frac{E_\infty}{(10^{38} \text{ erg sec}^{-1})} \right]^{1/2} \left[\frac{v_\infty}{(1000 \text{ km s}^{-1})} \right]^{-1/2} \left[\frac{P_{\text{IGM}}}{K_B} \times (0.005 \text{ K cm}^{-3}) \right]^{-1/2} \left(\frac{\text{G}}{}\right)^{-1/2}. $$

This takes roughly $10$ Gyr for a $1000$ (10000) km s$^{-1}$ wind to traverse $1$ Mpc. Thus, galactic winds can transport energy deep into the IGM.

But suppose CRs are not advected out but simply diffuse from their host galaxies (as in GALPROP models)? CR diffusion results in a net flow out of the Galaxy only if the energy density outside is less than that inside. Since CRs do actually diffuse out of the Galaxy, the CR energy density in the distant Galactic halo is less than that within the disc. For a steady CR luminosity, we therefore have

$$\frac{t_{\text{MW}}}{V_{\text{out}}} = \frac{t_{\text{in}}}{V_{\text{in}}}. $$

The Milky Way has been forming stars for $t_{\text{MW}} \approx 10$ Gyr, whereas the time that CRs stay within the Galactic disc is only about $t_{\text{in}} \approx 30$ Myr (Connell 1998). The confinement volume of the Galactic disc is $V_{\text{in}} \gtrsim 350$ kpc$^3$ (S02). We can set limits on $V_{\text{out}}$, the confinement volume of CRs that have ‘escaped’ the Galaxy. Supposing that the CRs fill a sphere with radius $R_{\text{out}}$, I conservatively find:

$$R_{\text{out}} \gtrsim \frac{3 \times 10^{18}}{V_{\text{in}} t_{\text{AW}}^{1/3}} = 30 \text{ kpc} \left(\frac{V_{\text{in}}}{350 \text{ kpc}^3}\right)^{1/3}. $$

If CRs are not advected away, they must diffuse far beyond the Galactic disc, well into the circumgalactic gas.

3.2 How far in the IGM do they go?

The propagation of CRs depends on the IGMF strength and structure (Adams et al. 1997). Very little is known about the IGMF, other than that it less than $\lesssim 1 \mu$G for all coherence lengths and $\lesssim 1$ nG on large scales (Neronov & Vovk 2010). The most interesting constraints come from $\gamma$-ray observations. The lack of GeV cascade emission from blazars suggests that pair $e^\pm$ generated by TeV $\gamma$-rays on their way to Earth are deflected out of the sightline by IGMFs. This suggests a lower limit of $10^{-18}$ G (Dermer et al. 2011), but the applicability of the limits is disputed (Broderick et al. 2012).

Supposing that CRs do reach the large-scale IGM, Bohm diffusion represents the slowest possible propagation. The mean free path is $\lambda_{\text{CR}} = r_L \approx 1.1$ Mpc $p_{\text{GeV}}^{-1}/B_{-18}$, where $B = 10^{-18}$ $B_{-18}$ G. The distance CRs diffuse is then $s_{\text{Bohm}} = \sqrt{3\omega_{\text{CR}}t\lambda_{\text{CR}}} = 58$ Mpc $\sqrt{3\omega_{\text{CR}}t_0 p_{\text{GeV}}}/B_{-18}$. Note that $s_{\text{Bohm}} < 1$ kpc for $B > 10$ nG. Bohm diffusion is only an extreme limit, requiring big enough $\lambda_B$; CRs probably diffuse much farther than $s_{\text{Bohm}}$.

The maximum distance that CRs propagate into the IGM could be set by plasma waves that they excite while they stream. Within galaxies, where the magnetic energy density is comparable to thermal pressure, CRs self-confine themselves to speeds less than the Alfvén speed (Kulsrud & Pearce 1969). In the classical version of CR self-confinement, the magnetic fluctuations from CR streaming are much smaller than the mean field. However, it is thought that some non-linear version of the instability can amplify magnetic fluctuations until they are larger than the mean field to confine CRs if necessary (Lucch & Bell 2000).

The sound speed is much greater than the Alfvén speed in the IGM, though. In these conditions, the streaming speed of CRs is probably of order the sound speed $c_s = 15$ km s$^{-1}$, $\sqrt{T_2}$ (Holman, Ionson, & Scott 1979). This weak self-confinement limits the distance that intergalactic CRs stream to $s_{\text{confine}} = c_s t_0 = 0.15$ Mpc $t_0\sqrt{T_2}$. Note that in hot phases like the WHIM, the CRs can stream out fastest. For $T = 10^8$ K, $s_{\text{confine}} = 2$ Mpc, bigger than the typical size of a WHIM structure.

Even if wave generation slows down CRs, this is very interesting in itself: it means that CRs excite IGMFs where they reside. The CR mean free path is at least $r_L$. If their average streaming speed over a time $t_{\text{stream}}$ is $\lesssim c_s$, then the magnetic field fluctuation strength must be at least $B_{\text{CR}} eB/2(\epsilon_{\text{AW}} T_{\text{stream}})$, or $B \gtrsim 10^{-13}$ G $p_{\text{GeV}}^{1/3} (\epsilon_{\text{AW}} T_{\text{stream}}/(10$ Gyr$))^{-1}$ on some $\sim 10$ pc $p_{\text{GeV}}(B/10^{-13}$ G$)^{-1}$. Any magnetic fluctuations excited by CRs are no greater than $\sim \sqrt{8\pi UC_\text{CR}}$ on energetic grounds; for $z = 0$, this is $\lesssim 9 f_\phi\epsilon_{\text{SN}}$ nG for $\epsilon_{\text{adv}} = 1$ (escaping CRs) or $\epsilon_{\text{SN}} = 1$ (wind shock CRs).
4 CONCLUSIONS

The injection of CRs by SFGs into the IGM is a long-neglected kind of feedback. The energy in CRs accelerated by SFGs over the Universe’s history is comparable to the thermal energy in the Lyα forest. Although the CRs may experience strong adiabatic losses as they are advected away from SFGs by winds, some of that energy may be recovered in CRs at the winds’ termination shocks. The calculated pressure of intergalactic CRs is then still within an order of magnitude of that of the Lyα forest. If the CRs are trapped in a denser phase, their own density is also necessarily higher, meaning that these CRs are important if they end up in gas with $T \approx 10^{4}$ K and $\delta \lesssim 1000$. CRs may have been especially important at $z \gtrsim 1$, when the star-formation rate density was greatest and most of the IGM was cool.

If standard theories of CR streaming apply to the IGM, the CRs affect its magnetic structure. As they self-confine to roughly the sound speed, they excite magnetic fluctuations with $B \gtrsim 10^{-13}$ G. Even so, they can penetrate through up to 100 kpc of $10^{7}$ K gas and 1 Mpc of $10^{8}$ K gas.

SFGs are the not the only source of CRs in the IGM. Active galactic nuclei and structure formation accelerate CRs too. Rather, CRs from SFGs demonstrate the need to consider nonthermal processes in the IGM. The nonthermal fields may prove to be just as important to the IGM as in the interstellar medium.

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