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Ellen G. Zweibel

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The microphysics and macrophysics of cosmic rays[a)]

Ellen G. Zweibel[b)]
Departments of Astronomy and Physics and Center for Magnetic Self-Organization, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA

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This review paper commemorates a century of cosmic ray research, with emphasis on the plasma physics aspects. Cosmic rays comprise only $\sim 10^{-9}$ of interstellar particles by number, but collectively their energy density is about equal to that of the thermal particles. They are confined by the Galactic magnetic field and well scattered by small scale magnetic fluctuations, which couple them to the local rest frame of the thermal fluid. Scattering isotropizes the cosmic rays and allows them to exchange momentum and energy with the background medium. I will review a theory for how the fluctuations which scatter the cosmic rays can be generated by the cosmic rays themselves through a microinstability excited by their streaming. A quasilinear treatment of the cosmic ray–wave interaction then leads to a fluid model of cosmic rays with both advection and diffusion by the background medium and momentum and energy deposition by the cosmic rays. This fluid model admits cosmic ray modified shocks, large scale cosmic ray driven instabilities, cosmic ray heating of the thermal gas, and cosmic ray driven galactic winds. If the fluctuations were extrinsic turbulence driven by some other mechanism, the cosmic ray background coupling would be entirely different. Which picture holds depends largely on the nature of turbulence in the background medium. [http://dx.doi.org/10.1063/1.4807033]

I. INTRODUCTION

The hundredth year of cosmic ray astrophysics was commemorated in 2012. Carlson[1] gives a concise introduction to the early history. Although it was noticed by Coulomb in 1785 that ionizing radiation is present at the Earth's surface, it was not until 1912 that V. M. Hess showed that ionization increases with altitude, suggesting that it has a cosmic source. Whether the "cosmic rays" were photons or charged particles was not immediately clear, but by the l930s, as evidence accumulated that cosmic rays are deflected by the geomagnetic field, they were generally conceded to be charged particles. In 1934, Baade and Zwicky[2] made the prescient and still widely accepted suggestion that cosmic rays are energized by supernovae. In 1949, Fermi[3] published his theory of cosmic ray acceleration by randomly moving "magnetic clouds" and gave a general argument for how the joint action of acceleration and escape can lead to a power law energy spectrum. In the same year, Hiltner[4] and Hall[5] detected a pervasive galactic magnetic field through the alignment of interstellar dust, which polarizes starlight. Thus, by the middle of the last century, there was a firm basis for studying the plasma physics of cosmic rays. Cosmic ray acceleration, propagation in galactic and extragalactic magnetic fields, and feedback on the ambient medium have been prominent research topics ever since.

This is an excellent time to do research on cosmic rays. Recent progress in radio, γ-ray, and particle detection capabilities together with improved understanding of magnetic turbulence, energetic particle transport, reconnection, and collisionless shocks, and advances in computation are making it possible to develop and test theoretical ideas in unprecedented detail and with great rigor. Although traditionally there has been relatively little communication between the cosmic ray astrophysics and laboratory plasma physics communities, there are overlapping areas of interest, including particle transport in stochastic magnetic fields, mechanisms for particle heating and energization, and instabilities driven by energetic particles. Particle acceleration and propagation in the heliosphere offers its own challenges and allows key aspects of energetic particle interactions with waves, turbulence, and shocks to be observed close up or probed *in situ*.

This paper is primarily devoted to collective aspects of cosmic ray behavior, In Sec. II, I give a brief review of cosmic ray properties. In Sec. III, I show how the kinetic description of cosmic rays can be replaced by a fluid description in the limit of strong scattering by small scale electromagnetic fluctuations, and how cosmic rays themselves can generate the fluctuations which scatter them. In Sec. IV, I discuss some applications and implications of the fluid description, including Fermi acceleration of cosmic rays at shocks, cosmic ray driven galactic outflows, and cosmic ray heating of interstellar and intergalactic gas. In Sec. V, I summarize and point out some areas where more work is needed.

The subject is vast, and the reference list is not comprehensive. Many aspects of cosmic ray astrophysics are only briefly touched on here. For the properties and theories of origin of the highest energy cosmic rays, see Ref. 6. For high energy physics aspects, see Refs. 7 or 8. For propagation

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[b)]Invited speaker. Electronic address: zweibel@astro.wisc.edu

models, see Ref. 9. For properties of cosmic rays in the context of the interstellar medium, see Ref. 10. For a pedagogical introduction to some of the material presented here, see Ref. 12. Notable monographs on the plasma physics of cosmic rays include Refs. 13 and 14.

II. PROPERTIES OF COSMIC RAYS

Cosmic rays are detected directly at the Earth and in the heliosphere and observed remotely through electromagnetic emissions. The electron/positron component is measured through its synchrotron, inverse Compton, and relativistic bremsstrahlung emission. The ion component is observed indirectly at γ-ray wavelengths; the γ-rays are the decay products of pions produced in collisions between cosmic ray nuclei and interstellar particles. The γ-ray evidence is ambiguous, however, as γ-rays are also produced by electrons and positrons, through relativistic bremsstrahlung emission and inverse Compton scattering of background photons. Thus, it is not entirely clear that this high energy emission is hadronic in origin. Detection of high energy ν from these sources, however, would be strong evidence for energetic hadrons, and is one of the goals of high energy ν experiments such as IceCube.

Remote sensing has revealed that cosmic rays exist throughout the Galaxy, that their intensity increases slightly toward the Galactic Center, and that they occupy a disk a few kiloparsecs thick, several times thicker than the cold, dense component of the interstellar gas. Similar relativistic electron populations are detected through synchrotron emission from other galaxies and galaxy clusters, which serendipitously provides an opportunity to map galactic and intracluster magnetic fields. A number of nearby galaxies, and galaxies with active nuclei, have also been detected at γ-ray energies.

The existence of the thick synchrotron disk directly demonstrates that the Galactic magnetic field, too, extends well above the Galactic plane. It is known that near the midplane, the mean magnetic field is primarily horizontal and nearly azimuthal, but has a large random component. The orientation at high Galactic latitudes is less well measured, but a picture is beginning to emerge.[15–17] The mean and rms values of the interstellar magnetic field within a few kpc of the Sun are about 1.6 μG and 5 μG, respectively.[18] At these fieldstrengths, the gyroradius of a GeV proton is less than 10^{12} cm.

Cosmic rays can also be probed over time. Fossil cosmic ray tracks show that the solar cycle averaged flux of cosmic rays at the Earth has been constant for at least $\sim 5 \times 10^7$ yr.[19] The detection of light elements, thought to be cosmic ray spallation products, in the atmospheres of some of the oldest stars in the Galaxy, is taken as evidence that the material from which these stars formed was irradiated by cosmic rays.[20] Thus, there were cosmic rays in the Galaxy at or shortly after the time it formed.

A composite cosmic ray energy spectrum synthesized from many experiments is shown in Figure 1. From about 1 – 3 10^6 GeV, the cosmic rays are mostly protons and the spectrum is a power law with index 2.6. This part of the spectrum carries most of the cosmic ray energy. At low energies, the spectrum turns over. Propagation of these lower energy particles into the heliosphere is strongly affected by the solar wind, making their flux uncertain (see Ref. 21). Low energy cosmic rays (a few to 10 MeV), not shown in Figure 1, play an important role in collisionally heating and ionizing the interstellar medium, but they account for only a small fraction of the cosmic ray energy density.

At $\sim 3 \cdot 10^6$ GeV, the spectrum steepens. This feature is called the "knee" and may represent a transition in the acceleration or confinement mechanism, and/or in elemental composition. Around 10^9 GeV, the spectrum flattens—this feature is called the "ankle." The gyroradii of these particles in the Galactic magnetic field are comparable to or greater than the size of the Galaxy. Because they are not confined, maintaining their interstellar energy density with a Galactic source would require an improbably large energy input, so they are thought to be extragalactic in origin. Their acceleration and propagation pose a host of fascinating problems, but because they represent such a small fraction of cosmic rays by energy density and number, relatively little is said about them in this paper.

Figure 1 shows that only 1%–2% of cosmic rays are electrons. The number density of cosmic rays is so much smaller than the number density of interstellar thermal

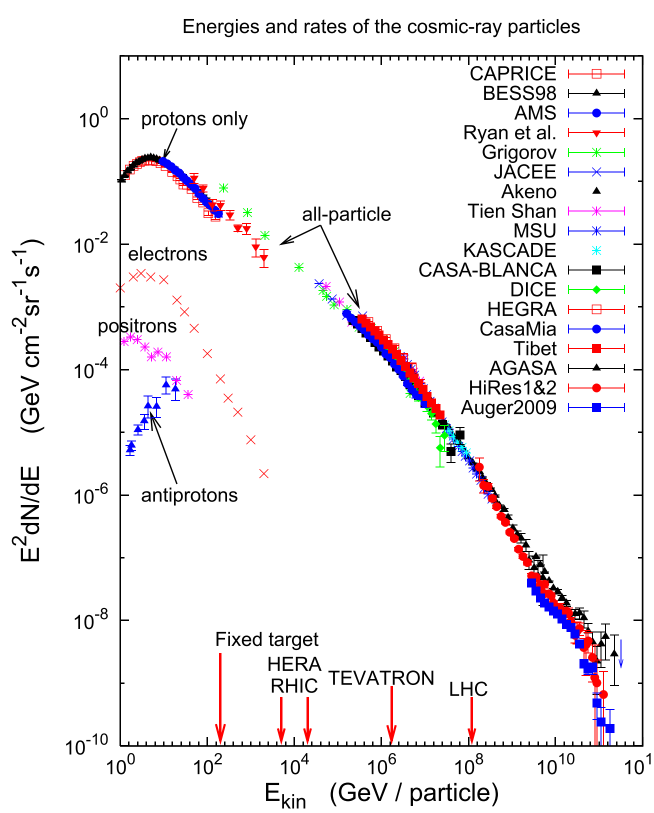

FIG. 1. The cosmic ray spectrum, by species, from 1 to 10^{12} GeV/particle. To convert to a distribution function in energy, multiply by $4\pi/(E^2 v)$, where v is particle velocity. The positrons and antiprotons are believed to be secondaries; products of nuclear collisions. The energy ranges of some major laboratory accelerators are shown for comparison, highlighting the importance of cosmic rays as high energy physics probes. Note the large number of different cosmic ray detection experiments, a tribute to the level of innovation and interest in this field. Courtesy of T. K. Gaisser with permission.

particles, and the bulk velocity is so small, that this nonneutrality does not pose a problem; the thermal electron current can easily cancel the cosmic ray current. The steeper slope of the electron spectrum relative to the proton spectrum is explained by the importance of radiative losses, and the E^2 dependence of synchrotron and inverse Compton radiative emission rates.

Measurements of cosmic ray composition constrain theories of cosmic ray acceleration and propagation. The abundances of the so-called *r*-process elements synthesized during core collapse supernova explosions are close to their interstellar values. This suggests that while supernovae are a plausible energy source for cosmic rays, cosmic rays are not themselves ejected by supernovae. There is a tremendous overabundance of the light elements; however, ^{3}He, Li, Be, and B are over-represented in cosmic rays (by 5–7 orders of magnitude at $\sim$1 GeV) relative to their interstellar abundances. The high abundances can be accounted for if cosmic rays undergo spallation reactions with 3–6 g cm^{-2} of interstellar material. When the spallation measurements are combined with ratios of unstable to stable isotopic species and interpreted by standard propagation models,[9] the result is a picture in which cosmic rays reside in the Galaxy for an energy dependent time which is $1 - 2 \cdot 10^7$ yr at 1 GeV and decreases as a low fractional power of energy.

Because the GeV cosmic ray lifetime is 3–4 orders of magnitude larger than the light travel time across the Galaxy, cosmic ray confinement must be very good. We can take this further. Cosmic rays are not primarily confined by the large scale magnetic geometry alone, because this would give too little dependence of lifetime on energy. Furthermore, the cosmic ray acceleration time is much shorter than the cosmic ray lifetime. Otherwise, the most energetic cosmic rays would also be the oldest, whereas the decrease in confinement time with energy implies that the more energetic cosmic rays are younger.

Additional confirmation of good confinement follows from the observation that the distribution of cosmic ray arrival directions at Earth is isotropic to a few parts in 10^4 at GeV energies, with the anisotropy increasing slowly with energy. This argues that cosmic rays propagate too randomly to be traced back to their sources (an estimate of the residual imprint of local sources is given in Ref. 22). However, low amplitude patches of enhanced and reduced flux have recently been detected at TeV energies;[23–25] they may be signatures of local galactic sources,[26] or due to processes in the heliosphere.[27,28]

In summary, a variety of data sources, *in situ* and remote, have led to a canonical cosmic ray scenario according to which cosmic rays are drawn from the pool of thermal interstellar gas, accelerated in a relatively short amount of time by a process that favors ions over electrons and propagated diffusively through the interstellar medium with a diffusion coefficient that increases with increasing energy. It can be inferred from simple random walk arguments that the ratio of the scattering mean free path λ to the size of the system is approximately the ratio of the free streaming time to the confinement time. Thus, λ is a few parsecs for cosmic rays of a few GeV, and the corresponding diffusivity is of order 10^{28-29}cm^{2}s^{-1}.

In the remainder of this paper, we discuss the physical basis for this cosmic ray diffusion, and how it couples cosmic rays to the ambient medium.

III. FROM KINETIC TO FLUID THEORY

The distribution function $f(\mathbf{x}, \mathbf{p}, t)$ for any species of cosmic ray is governed by the Boltzmann equation

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \frac{d\mathbf{p}}{dt} \cdot \nabla_{\mathbf{p}} f = \frac{df}{dt}\Big|_c + S(\mathbf{x}, \mathbf{p}, t), \tag{1}$$

where

$$\frac{d\mathbf{p}}{dt} = q\left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right) \tag{2}$$

is the usual Lorentz force. The first term on the right hand side of Eq. (1) accounts for collisional processes such as spallation reactions and pion production. Collisions are included in cosmic ray propagation codes such as GALPROP[29] and are essential for comparing cosmic ray propagation models with data and for predicting radiative emission by cosmic rays. However, we ignore these terms here and concentrate on plasma effects. The second term on the right hand side of Eq. (1) is a source term. For the reasons discussed in Sec. II, the sources are thought to be localized in space and time.

Even if we had an exact model of electromagnetic fields in the Galaxy, solving Eq. (1) by direct integration of particle orbits for the bulk population of cosmic rays would be infeasible. The gyroradii of GeV cosmic rays are 9–10 orders of magnitude smaller than the size of the Galaxy, so a prohibitively large dynamic range would be required (deflection of ultra high energy cosmic rays by the large scale Galactic magnetic field can be calculated directly, however, Ref. 30). Therefore, we must resort to statistical treatments, and make some approximations.

A. Fieldline geometry

Beginning in the 1960 s, the astrophysics and space physics communities devoted considerable effort to studying the propagation of test particles in random magnetic fields[31–34] with the goal of relating the spatial spreading of cosmic rays to statistical descriptions of fieldline wandering. In the limit that cosmic rays follow the fieldlines, they can wander perpendicular to the *mean* magnetic field no faster than the fieldlines themselves wander with respect to the mean. Scattering the cosmic rays along the fieldlines reduces the rate of perpendicular wandering. And, if the magnetic field varies significantly across a gyroradius, cosmic rays can cross the exact field, not just the mean field (they also cross fieldlines due to drifts, but the guiding center drifts v_{gc} associated with the global gradients in the Galactic magnetic field are very slow; $v_{gc}/v \sim 10^{-9} - 10^{-10}$ for GeV particles). For short recent reviews of cross field transport, see, e.g., Refs. 35 and 36. Issues related to particle transport in stochastic magnetic fields have long been discussed from a laboratory plasma perspective as well.[38]

Recently our understanding of interstellar MHD turbulence has improved and high resolution simulations of MHD turbulence have become available. This has led to renewed efforts to study both cross field and parallel propagation in realistic models of interstellar turbulence; see Ref. 37. Such studies are particularly important for calculating the propagation of higher energy cosmic rays, which are more sensitive to the structure of the magnetic field because of their larger gyroradii and longer scattering mean free paths.

B. Wave-Particle Interactions

A complementary approach to cosmic ray propagation, also initiated in the 1960s, ignored spatial diffusion due to the large scale fieldline geometry and focussed on how cosmic rays interact with small scale fluctuations superimposed on a uniform background magnetic field.[39,40] Since the mean free path is much larger than the cosmic ray gyroradius which in turn is much larger than kinetic scales in the thermal plasma, we anticipate that the fluctuations are primarily small amplitude MHD waves. Resonant scattering is expected to be particularly strong. The two relevant resonances are the Landau resonance

$$\omega - k_{\parallel} v_{\parallel} = 0 \tag{3}$$

associated with magnetosonic waves, and the gyroresonances

$$\omega - k_{\parallel} v_{\parallel} = n\Omega, \tag{4}$$

where "$\parallel$" means parallel to the mean magnetic field, ω and $k_{\parallel}$ are the frequency and parallel wavenumber of the fluctuation, $v_{\parallel}$ and Ω are the cosmic ray parallel velocity and relativistic gyrofrequency, and n is a positive or negative integer. We expect $\omega \sim kv_A$ for MHD fluctuations while $v \sim c$. Therefore, the Landau resonance requires either $k_{\perp}/k_{\parallel} \gg 1$ or $\mu \equiv v_{\parallel}/v \ll 1$. By similar reasoning, we can approximate the gyroresonance condition by $k_{\parallel} v_{\parallel} \sim n\Omega$, i.e., the scale of gyroresonant fluctuations is of order the cosmic ray gyroradius.

Because the interstellar medium is thought to be turbulent, it is natural to ask whether the MHD turbulent cascade by itself is sufficient to scatter the cosmic rays. The driving scale for MHD turbulence is probably tens of parsecs, far above the gyroresonant scale of GeV cosmic rays. Due to the presence of a strong mean Galactic magnetic field, the interstellar MHD turbulent cascade is expected to be highly anisotropic, with $k_{\perp}/k_{\parallel}$ increasingly large as the scale decreases below the driving scale. Gyroresonant fluctuations with $k_{\perp}/k_{\parallel} \gg 1$ are inefficient at scattering cosmic rays, because the fluctuating fields undergo many reversals over a gyro-orbit, leading to near cancellation of the fluctuating force. Therefore, the interstellar Alfvén wave cascade alone is not a major source of cosmic ray scattering. Recognition of this problem led to proposals for scattering due to magnetic mirroring from regions where the interstellar magnetic field becomes constricted,[41] or by scattering from magnetosonic waves generated by compressibility effects in the cascade.[42] In earlier work, scattering by magnetosonic waves was generally discounted because these waves are more readily damped than shear Alfvén waves. Without including damping—particularly collisionless damping—in the simulations which follow the generation of compressive waves, it is difficult to know their amplitude, and the level of cosmic ray scattering which they can provide.

One consequence of scattering by extrinsic turbulence is that energy flows from the turbulence to the particles. This can be described as second order Fermi acceleration[115] and can be an important damping mechanism for interstellar turbulence.[43]

There is an alternative, however. A gyroresonant instability driven by cosmic ray streaming anisotropy, discovered in the 1960 s by Refs. 39 and 40 transfers energy and momentum from cosmic rays to waves. In a steady state, the thermal background plasma must extract energy and momentum from the waves at the rate it is added by the cosmic rays. This instability, and the wave-particle interactions associated with it, forms the basis for cosmic ray self-confinement theory, and for the theory of how cosmic rays interact with the thermal background collisionlessly.

The effect of cosmic rays on small amplitude hydromagnetic waves is found in the usual way. One solves the linearized Vlasov equation for the perturbed cosmic ray distribution function in the presence of the wave electromagnetic fields and includes the cosmic ray contribution to the plasma dielectric function in deriving the dispersion relation. For the low cosmic ray number densities typically encountered in the interstellar medium, the effect of cosmic rays on the real part of the dispersion relation is negligible and it is only necessary to consider the effect of the cosmic rays on growth or damping (for a treatment that is valid at high energy densities see Refs. 44 and 45 and Sec. IV). The growth rate for linearly polarized waves propagating parallel to the background magnetic field (which grow faster than oblique waves) can then be written in the wave frame as[46]

$$\Gamma_{cr} = \frac{\pi^2}{2}\frac{q^2 v_A}{ck}\int \frac{v(1-\mu^2)}{cp} \times \left[\delta\left(\mu + \frac{m\Omega_0}{kp}\right) + \delta\left(\mu - \frac{m\Omega_0}{kp}\right)\right]\frac{\partial f}{\partial \mu} d^3p, \tag{5}$$

where Ω_0 is the nonrelativistic gyrofrequency for particles of that species. Equation (5) is written in coordinates such that $d^3p = p^2 dp d\mu d\phi$ with $\mu \equiv \mathbf{p}\cdot\mathbf{B}/pB = p_{\parallel}/p$ being the cosine of the particle pitch angle. For simplicity, we only consider one species of cosmic rays, but it is straightforward to extend the results to a sum over species. The δ-functions encode the resonance conditions for the left and right circularly polarized components of the wave (Eq. (4) with ω dropped).

Equation (5) shows that waves propagating in the positive direction grow if the cosmic rays have a positive anisotropy in their frame ($\partial f/\partial \mu > 0$), are damped if the anisotropy is negative, and are neutrally stable if the distribution is isotropic. We also see that only cosmic rays above a minimum momentum $p_{min} \equiv m\Omega_0/k$ can resonate with waves of wavenumber k. Carrying out the integration over μ brings Eq. (5) to the form

$$\Gamma_{cr} = \frac{\pi^2}{2}\frac{q^2 v_A}{ck}\int_0^{2\pi} d\phi \int_{p_{min}}^{\infty} (p^2 - p_{min}^2)\frac{v}{cp} \times \left[\frac{\partial f}{\partial \mu}|_{p_{min}/p} + \frac{\partial f}{\partial \mu}|_{-p_{min}/p}\right] dp, \tag{6}$$

which is an integral over only those cosmic rays energetic enough to resonate with the wave. For a power law distribution $f \propto p^{-\alpha}$, the integral takes a simple form, and can be written as[47]

$$\Gamma_{cr} = \frac{\pi}{4}\frac{\alpha - 1}{\alpha}\Omega_0 \frac{n_{cr}(> p_{min})}{n_i}\left(\frac{v_D}{v_A} - 1\right), \tag{7}$$

where n_i is the ion density of the ambient plasma and v_D is the streaming velocity of cosmic rays along the background magnetic field. For cosmic rays of a few GeV, and $(v_D/v_A - 1) \sim 1$, growth times are a few 10^{10} s under average interstellar conditions. This is long compared to the wave periods (typically of order a year), justifying the weak damping approximation made in deriving Eq. (5), but short compared to typical macroscopic interstellar timescales, suggesting that the waves adjust quickly to local conditions. Near the strong shocks thought to be responsible for cosmic ray acceleration, the cosmic ray flux $n_{cr}v_D$ is several orders of magnitude larger, making wave growth correspondingly faster.

Because the phase space density of cosmic rays declines rather steeply with p ($\alpha \sim 4.6$ for Galactic cosmic rays in the few GeV range), most of the amplification of a wave with wavenumber k is due to cosmic rays with $p \approx p_{min}(k)$. Likewise, because $n_{cr}(> p_{min}) \propto p_{min}^{1-\alpha} \propto k^{\alpha-1}$, Γ_{cr} declines rapidly with increasing particle energy. Since some source of wave damping is always present, we should expect that cosmic rays above a certain energy will be unable to generate enough waves to confine themselves.

It is also interesting to consider how minority ions with $Z \neq 1$ will interact with the waves. A nucleus with $Z > 1$ and relativistic energy E interacts with the same waves as a proton with energy E/Z, and Γ_{cr} at the resonant k is larger than Γ_{cr} for waves which scatter protons of the same energy as that heavy nucleus.

Now we consider the effect of the waves on the cosmic rays. As first demonstrated in Ref. 48, the wave-particle interaction can be described as diffusion in momentum space. It was shown in Ref. 40 that scattering in μ dominates scattering in p by a factor of order $(c/v_A)^2$. Keeping only resonant pitch angle scattering is equivalent to working in the wave frame if only waves propagating in one direction are present. Averaging over gyrophase, the Boltzmann equation for F, the phase averaged part of the cosmic ray distribution function is found to be

$$\frac{\partial F}{\partial t} + \mathbf{v}\cdot\nabla F = \nabla_{\mathbf{p}}\cdot\mathbf{D}_{\mathbf{pp}}\cdot\nabla_{\mathbf{p}}F + S \approx \frac{\partial}{\partial \mu}\frac{\nu(1-\mu^2)}{2}\frac{\partial F}{\partial \mu} + S, \tag{8}$$

where the approximation consists of keeping only diffusion in μ. The scattering frequency $\nu(p, \mu)$ is

$$\nu(p,\mu) = \frac{\pi}{4}\Omega\frac{k\mathcal{E}(k)}{B_0^2/8\pi}, \tag{9}$$

with the gyroresonance condition $k = \Omega/(\mu v)$, and $k\mathcal{E}(k)$ the wave energy at wavenumber k.

Equation (9) has a straightforward physical interpretation: ν is of order $\Omega(\delta B/B_0)^2$, where δB is the fluctuation amplitude at the resonant wavelength. If we associate the angle by which the fieldlines are bent, $\delta B/B_0$, with the rms scattering angle $\delta\theta$, and assume the particles encounter uncorrelated waves at frequency Ω, then the angular diffusion coefficient $\langle(\delta\theta)^2\rangle/\delta t \sim \Omega(\delta B/B_0)^2$, which is essentially Eq. (9).

This interpretation breaks down, however, as $\mu \to 0$ and reversing direction becomes a consideration. There are two reasons for this. One is that the scattering process is based on a perturbation theory in which one integrates along the unperturbed orbits. Reversal of direction is a large effect, outside the scope of perturbation theory. The other reason is that particles with $|\mu| \ll 1$ interact with very short wavelength waves, and there is little power at these wavelengths. It was shown in Ref. 49 that below some critical μ_c, mirroring by longer wavelength waves is more important than scattering by gyroresonant waves, and leads to a small correction to the scattering frequency.

The scattering term in Eq. (8) acts like friction to bring the cosmic ray mean parallel velocity to rest in the wave frame. This can be shown by multiplying Eq. (8) by μp and integrating over momentum space. Integrating the scattering term on the right hand side by parts yields

$$\frac{\partial}{\partial t}\int \mu p F p^2 dp d\mu + \nabla\cdot\int \mathbf{v}\mu p F p^2 dp d\mu = -\int \frac{p\nu(1-\mu^2)}{2}\frac{\partial F}{\partial \mu}p^2 dp d\mu + \int p\mu S p^2 dp d\mu. \tag{10}$$

The first term on the left hand side of Eq. (10) is the rate of change of parallel momentum density $\mathbf{P}_{cr}\cdot\mathbf{B}/B$. The second term can be split in the usual way into the divergence of the Reynolds stress and the divergence of the pressure tensor (which is usually assumed to be isotropic). The right hand side is opposite in sign to the parallel momentum density and also to the growth rate of the waves (Eq. (5)). This shows that the growth of the waves is accompanied by parallel momentum loss by the cosmic rays.

In the wave frame, the fluctuations are static, so the cosmic ray energy density U_{cr} does not change. This can be seen explicitly by multiplying Eq. (8) by the particle energy ϵ and integrating over momentum space; the scattering term integrates to zero. Transforming to the lab frame, and assuming $v_A/c \ll 1$, one expects dU_{cr}/dt to be $\mathbf{v}_A\cdot d\mathbf{P}_{cr}/dt = \mathbf{v}_A\cdot\nabla P_{cr}$. Alternatively, one can work in the lab frame and retain the small terms in the diffusion tensor $\mathbf{D}$ introduced in Eq. (8) which account for changes in p. If all the waves are moving down the cosmic ray density gradient, i.e., streaming at the Alfvén speed in the same direction as the cosmic rays, the two approaches are equivalent.

The near isotropy of cosmic rays implies that their mean velocity is much less than their random velocity, so the inertial and Reynolds stress terms are much less than the pressure term, and are usually dropped. In that case, the momentum transferred by scattering is proportional to the cosmic ray pressure gradient, resulting in a force $-\nabla_{\parallel} P_{cr}$ in the thermal gas and a heating rate $v_A \nabla_{\parallel} P_{cr}$.

Although Eq. (10) suggests that the waves act to make the cosmic rays isotropic in the wave frame, this is not achieved in practice. The source term tends to make f anisotropic due to the concentration of supernovae near the Galactic plane; on an average, S should decrease with Galactic latitude and has strong local gradients near cosmic ray acceleration sites as well. Furthermore, as discussed in Sec. IV, a variety of mechanisms can damp the waves, so neutral stability lies above the streaming instability threshold. In a steady state, or in a time averaged sense, there should be a balance between the transport and source terms in Eq. (8) and between the growth rates and damping rates of waves. Therefore, in a steady state, Eq. (10) describes the transfer of momentum from the cosmic rays to the thermal background gas, mediated by the waves. In the lab frame, as argued above, this is accompanied by energy transfer, which appears as heat.

In summary, we have now shown that cosmic ray velocity space anisotropy can destabilize hydromagnetic waves through gyroresonant interaction, that the waves drive the cosmic rays toward isotropy in the wave frame and extract momentum and energy from them, and that as long as the waves are in a steady state, the momentum and energy extracted from the cosmic rays is transferred to the thermal gas.

C. Fluid equations

In Sec. II, we argued that the long confinement times and near isotropy of cosmic rays imply that they are well scattered: $\nu L/c \gg 1$. We now show that in this limit, Eq. (8) can be solved approximately, that there is a direct relationship between the cosmic ray anisotropy and spatial density gradient and that this implies that the cosmic rays behave as a diffusive fluid and are coupled to the thermal background.

Following Ref. 40, we consider a 1D model with $\mathbf{v}\cdot\nabla F = \mu v \partial F/\partial s$ and assume that there are three well separated timescales in the problem. The scattering timescale ν^{-1} is shortest, the advective timescale L/c is intermediate, and the evolution, or source timescale, is longest. We then write $F = F_0 + F_1 + F_2 + \ldots$ and balance terms of comparable order such that Eq. (8) becomes a hierarchy, the first three equations of which are

$$0 = \frac{\partial}{\partial\mu}\frac{\nu(1-\mu^2)}{2}\frac{\partial F_0}{\partial\mu}, \tag{11}$$

$$v\mu\frac{\partial F_0}{\partial s} = \frac{\partial}{\partial\mu}\frac{\nu(1-\mu^2)}{2}\frac{\partial F_1}{\partial\mu}, \tag{12}$$

$$\frac{\partial F_0}{\partial t} + \mu v\frac{\partial F_1}{\partial s} = \frac{\partial}{\partial\mu}\frac{\nu(1-\mu^2)}{2}\frac{\partial F_2}{\partial\mu} + S. \tag{13}$$

The solution to Eq. (11) is $\partial F_0/\partial\mu = 0$; to lowest order, the cosmic rays are isotropic. Substituting this result into Eq. (12) and integrating over μ' from μ to 1 gives an expression relating the anisotropy to the density gradient

$$\frac{\partial F_1}{\partial\mu} = -\frac{v}{\nu}\frac{\partial F_0}{\partial s}. \tag{14}$$

Substituting Eqs. (14) into Eq. (13) and integrating over μ between ∓ 1 leads to a spatial diffusion equation for F_0

$$\frac{\partial F_0}{\partial t} - \frac{\partial}{\partial s}D_{\parallel}\frac{\partial F_0}{\partial s} = \frac{1}{2}\int_{-1}^{1} S d\mu, \tag{15}$$

where

$$D_{\parallel} \equiv \int_{-1}^{1}\frac{v^2(1-\mu^2)}{4\nu}d\mu \tag{16}$$

is the coefficient of diffusion along the magnetic field. It can be evaluated for a power law spectrum of waves and is often taken to be a power law in momentum.

Equation (15) was generalized in Ref. 46 to include flow of the background plasma. If the plasma speed is $\mathbf{U}$, then the wave speed $\mathbf{w}$ in the lab frame is $\mathbf{w} = \mathbf{U} + v_A\mathbf{b}$, where $\mathbf{b} \equiv \mathbf{B}_0/B_0$. Through an ordering scheme similar to that leading to Eq. (15), Ref. 46 derived the more general equation

$$\frac{\partial F_0}{\partial t} + \mathbf{w}\cdot\nabla F_0 - \frac{1}{3}(\nabla\cdot\mathbf{w})p\frac{\partial F_0}{\partial p} - \nabla_{\parallel}(D_{\parallel}\nabla_{\parallel}F_0) = 0. \tag{17}$$

The source term S has been omitted from Eq. (17), but it could easily be added.

Equation (17) leads to fluid equations with intuitively plausible properties. Integrating over momentum space yields the usual continuity equation for a diffusive fluid with $\mathbf{w}$ playing the role of fluid velocity

$$\frac{\partial n_{cr}}{\partial t} + \nabla\cdot(n_{cr}\mathbf{w}) = \nabla_{\parallel}(\mathcal{D}_n\nabla_{\parallel}n_{cr}), \tag{18}$$

where n_{cr} is the number density of cosmic rays and $\mathcal{D}_n$,the momentum averaged spatial diffusion coefficient, is

$$\mathcal{D}_n \equiv \frac{\int D_{\parallel}\nabla_{\parallel}F_0 p^2 dp}{\int \nabla_{\parallel}F_0 p^2 dp}. \tag{19}$$

Multiplying Eq. (17) by particle energy ϵ and integrating over momentum yields an equation for U_{cr}, the energy density in cosmic rays

$$\frac{\partial U_{cr}}{\partial t} = -\nabla\cdot[\mathbf{w}(U_{cr}+P_{cr})] + \mathbf{w}\cdot\nabla P_{cr} + \nabla_{\parallel}(\mathcal{D}_{\epsilon}\nabla_{\parallel}U_{cr}), \tag{20}$$

where we have integrated the third term in Eq. (17) by parts and used $v = d\epsilon/dp$. The first term on the right hand side is the divergence of the cosmic ray enthalpy flux; second term is the work done on the thermal gas, and the third term represents diffusion, with diffusion coefficient

$$\mathcal{D}_\epsilon \equiv \frac{\int D_\parallel \epsilon \nabla_\parallel F_0 p^2 dp}{\int \epsilon \nabla_\parallel F_0 p^2 dp}. \tag{21}$$

If F_0 and $D_\parallel$ are powerlaws in p, $\mathcal{D}_n$, and $\mathcal{D}_\epsilon$ are the same to order unity.

The fluid model has been extended to include cosmic ray viscosity.[50] The derivation follows a collisional approach to scattering reminiscent of gas kinetic derivations of viscosity rather than the wave based quasilinear approach of Ref. 46 or 40. A full calculation along the lines of Ref. 51 based on a wave-particle interactions does not seem to be in the literature.

Before passing on to the applications, one detail needs to be cleared up: the coupling of cosmic rays and thermal gas perpendicular to the background magnetic field. If we neglect cross field transport and cosmic ray inertia, then the perpendicular components of the cosmic ray momentum equation reduce to

$$\nabla_\perp P_{cr} = \frac{\mathbf{J}_{cr} \times \mathbf{B}}{c}. \tag{22}$$

Using Ampere's Law, Eq. (22) can be rewritten as

$$\nabla_\perp P_{cr} = \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi} - \frac{\mathbf{J}_{th} \times \mathbf{B}}{c}, \tag{23}$$

where $\mathbf{J}_{th}$ is the current in the thermal plasma. When Eq. (23) is added to the thermal plasma momentum equation, the thermal current term cancels, and $-\nabla_\perp P_{cr}$ appears as a force on the thermal gas.

IV. APPLICATIONS

The theory described in Sec. III has been applied to a diverse set of astrophysical problems. The discussion here is not exhaustive, but meant to provide the flavor of what can be done.

A. Cosmic ray self confinement

First came an assessment of the streaming instability for cosmic ray self-confinement.[40,46,47] The cosmic rays are considered self confined if the streaming anisotropy v_D at which the rate of wave growth (Eq. (7)) balances the rate of wave damping is not too large. Thus, it is necessary to consider how the waves are damped.

Ion-neutral friction was the first damping mechanism considered. Most of the mass of the interstellar medium is less that 1% ionized. Because the ion-neutral collision frequency is typically much less than frequencies of gyroresonant hydromagnetic waves, the waves propagate in the plasma alone and are damped by collisions with neutrals at the rate

$$\Gamma_{in} = \frac{1}{2} \frac{m_n n_n \langle \sigma v \rangle_{in}}{m_i + m_n}. \tag{24}$$

It was shown that the observed anisotropy and ages of GeV cosmic rays are consistent with the theory and with the thickness of the Galactic disk (Eq. (14)) up to about 100 GeV, but that above this energy there are too few cosmic rays to resonantly amplify the waves, and self-confinement fails.

This conclusion has been reinforced by the discovery of other damping mechanisms which operate in fully ionized gas. One is nonlinear Landau damping.[12,52] This occurs when thermal ions have a Landau resonance with the beat wave formed by superimposing two of the cosmic ray generated waves. The damping rate is

$$\Gamma_{nl} = \left(\frac{\pi}{8}\right)^{1/2} k v_i \frac{8\pi k \mathcal{E}}{B^2}, \tag{25}$$

where $k\mathcal{E}$ is defined below Eq. (9).

Inhomogeneity of the background magnetic field also leads to wave damping. Curvature and gradients in the large scale field mix the Alfvén and magnetosonic modes, making the gyroresonant waves subject to transit time damping and parallel viscous damping by the thermal plasma,[44,113,114] More recently, it was proposed that the waves are damped by shearing due to the small scale perpendicular magnetic structure associated with the MHD turbulent cascade,[42,53] A wave with transverse wavenumber, $\lambda_\perp$ is sheared apart at the eddy turnover rate at that scale; $v_\perp(\lambda_\perp)/\lambda_\perp$. The smallest possible $\lambda_\perp$ for a cosmic ray generated wave is dictated by the turbulent amplitude $\delta B(\lambda_\perp)$ at the gyroresonant scale: $\lambda_\perp \sim \lambda_\parallel (\delta B(\lambda_\perp)/B$. For the MHD cascade derived in Ref. 54, the minimum turbulent damping rate is estimated to be

$$\Gamma_{turb} \sim \frac{k v_A}{(kL)^{1/2}}, \tag{26}$$

where L is the driving scale of the turbulence and the inertial range is assumed to extend to the gyroresonant scale.

When nonlinear Landau damping and turbulent damping in fully ionized regions are considered together with ion-neutral friction in partially ionized regions, it appears that cosmic rays are not self confined above 100 GeV anywhere in the interstellar medium. Ion-neutral friction is so strong that not even the lower energy cosmic rays are self confined in the dense, cold clouds that occupy a small fraction of the interstellar volume but most of the interstellar mass.[55] We return to some implications of this in the following sections.

B. Acceleration at shocks

Self confinement operates under extreme conditions at strong shocks where cosmic rays undergo acceleration; see Refs. 56–59 for the original basic papers and Refs. 11 and 60–62 for reviews. Although the diffusive shock acceleration theory, we are about to describe is arguably the leading theory for the origin of galactic cosmic rays, it cannot be considered a fully established theory; see Refs. 63–65 for discussions of some current observational and theoretical problems. And, although shocks may be the energy source for cosmic ray acceleration, there are alternative mechanisms for accelerating cosmic rays in the vicinity of shocks. These include drift along the electric field of nearly perpendicular shocks and reconnection of magnetic fields compressed or tangled by the shocks. We will not discuss these mechanisms here, however.

Acceleration by a quasi-parallel shock is a form of first order Fermi acceleration. Consider a steady shock with speed $v_s \gg v_A$ and compression ratio R. In the shock frame, unshocked fluid streams toward the shock at speed V_S and shocked fluid streams away at speed v_S/R. Thus, a particle which executes a complete loop (scattered from upstream to downstream and back again, or *vice versa*) gains energy $2pv_S(R-1)/R$. The strong upstream anisotropy of cosmic rays generates waves which confines the particles to a layer of order $D_{\parallel}/v_S$ at the shock, allowing them to complete of order c/v_s loops before diffusing away from the shock layer.

If the shock is idealized as a discontinuity with the upstream and downstream flow properties connected by the Rankine-Hugoniot conditions, and if it is assumed that scattering maintains the particles near isotropy, the resulting spectrum is a power law: $f(p) \propto p^{-3R/(R-1)}$. Since $R \rightarrow 4$ in the limiting case of a strong shock in an ideal gas, the predicted spectral index -4 in momentum space or -2 in energy space is in good agreement with the Galactic cosmic ray spectrum (energy dependent losses steepen the spectrum somewhat). This is not a coincidence. Fermi[3] gave a general argument showing that if the rate at which a particle gains energy is proportional to the energy of the particle itself, the energy spectral index should be 1 plus the ratio of the acceleration time to the escape time. In diffusive shock acceleration these times are similar.

The amplitude of the spectrum is not predicted by this simple test particle theory, however. To estimate the efficiency of shock acceleration it is necessary to develop a nonlinear treatment in which the cosmic rays and the waves which scatter them react back on the fluid flow. In the quasilinear treatment of wave-particle interaction, and the fluid equations which follow from it, the cosmic ray back reaction leads to a precursor in which the incoming fluid is slowed due to momentum deposition by the cosmic rays, and the compression ratio R is increased due to transfer of energy to escaping cosmic rays. This hardens the spectrum and limits the efficiency to something like 10%–20% of the shock energy going into cosmic rays.[26,66–72]

An important modification of self confinement theory arose from the discovery of another transverse electromagnetic instability driven by cosmic rays. This instability also requires super-Alfvénic cosmic ray streaming, but is driven by the thermal electron current that is assumed to flow in the background to cancel the cosmic ray current.[44,45,73–79] The instability occurs when the cosmic ray energy density U_{cr}, background magnetic energy density U_B, and cosmic ray streaming velocity v_D satisfy the inequality $U_{cr}/U_B > c/v_D$. When this criterion is satisfied, the wavelength of the fastest growing mode is below the gyroradius of GeV cosmic rays. The cosmic rays do not $\mathbf{E} \times \mathbf{B}$ drift in the wave fields, and the wave is driven by unbalanced perturbed electron current. Numerical PIC and hybrid simulations suggest the instability produces large amplitude current filaments, possibly because of the net helicity of the fluctuations[80] (only one component of circular polarization is unstable). The result is that the magnetic field in the vicinity of the shock is significantly amplified, far above what would be expected due to compression of the ambient interstellar magnetic field alone.

The possibility of magnetic field amplification at the shock addresses two quite separate problems suggested by observations. The maximum rate at which particles can be accelerated by the first order Fermi effect in shocks was shown in Ref. 81 to be of order $0.15ZeBv_S^2/c$. Generally V_S declines over time as the shock expands; thus, there is a well defined maximum particle energy that can be achieved by even an infinite planar shock; the finite size of the shock imposes additional constraints. For Galactic supernova remnants, this energy is short of the cosmic ray knee energy by at least an order of magnitude. If the magnetic field were amplified, acceleration would be faster, confinement would be better, and the knee might be reached. Completely independently, observations of young supernova remnants show thin shells of x-ray emission which are thought to be synchrotron radiation from cosmic ray electrons with very short lifetimes. The short lifetimes require a strong magnetic field, much larger than expected from shock compression of the interstellar magnetic field.[82] This could be evidence for amplification of the field by cosmic rays.

Two points are worth noting before we leave shock acceleration. One is that it is not clear that the essential features of these intrinsically kinetic effects can be captured by a fluid theory such as is developed from the quasilinear picture. The other point is that cosmic rays are not the only possible driver of magnetic field amplification. When a shock propagates into a magnetized medium with clumpy structure, baroclinic effects create strong vortical turbulence which can amplify the magnetic field as well.[83,84]

C. Large scale equilibrium and stability

Cosmic rays have dynamical and thermal effects on the interstellar medium of our own and other galaxies and on the gas in galaxy clusters (intracluster medium). Since the Galactic cosmic ray pressure is roughly in equipartition with thermal gas pressure and magnetic pressure, we expect cosmic rays to have a strong dynamical effect provided that they couple to the rest of the medium (their energy density is thought to be below equipartition in galaxy clusters however). Through perpendicular coupling, described by Eq. (22), they provide vertical support to the galactic disk, approximately doubling the pressure gradient force exerted by the primarily horizontal galactic magnetic field and increasing the vertical scale height of the gas above what it would be for thermal pressure support alone.

The resulting stratification can be unstable.[85] The free energy source for the instability, which is known as the Parker instability, is the gravitational potential energy of thermal gas supported above its natural scale height. Stabilizing effects include magnetic tension associated with fieldline bending and work done to compress the gas as it is lowered; thus the stability criterion is sensitive to the compressibility of the composite thermal/cosmic ray fluid.

Early treatments of the Parker instability predated the parallel coupling picture discussed in Sec. III and assumed cosmic rays rearrange themselves instantaneously along the fieldlines. In this case, no work is done to compress them; they contribute only destabilizing buoyancy. Later work incorporated the fluid picture and accounted for cosmic ray compressibility, but not diffusion.[86] More recent treatments include cosmic ray diffusion.[87–90]

Simulations which follow the instability to nonlinear amplitude suggest that the combination of magnetic and cosmic ray driven buoyancy can play an important role in restructuring the Galactic magnetic field, and possibly in the Galactic dynamo[91,92] (see Ref. 93 for a critical discussion of magnetic flux escape from the Galaxy, however).

The Parker instability can be driven by magnetic buoyancy alone and does not require cosmic rays. Uniquely cosmic ray driven instabilities result from parallel coupling alone, however. These instabilities arise in the fluid approximation, and thus must be studied on scales large compared to the cosmic ray mean free path. An overstability of compressive waves driven by the cosmic ray pressure gradient was found in Ref. 94. It is expected to operate near shocks, where a large cosmic ray pressure gradient is a natural consequence of efficient shock acceleration. Acoustic waves can also be destabilized by cosmic ray heating and momentum transport, however, if the cosmic rays stream sufficiently fast, independent of their pressure gradient.[95] In their nonlinear stages, these instabilities can form weak shocks.[96–98] Their significance for cosmic ray acceleration and magnetic field evolution was recently reviewed in Ref. 79.

D. Winds and heating

In the hydrodynamic theory, cosmic rays can drive steady flows. The driving is both direct, through the pressure gradient, and indirect, through heating. Many recent detections of galactic winds, and the recognition that they play a significant role in the evolution of galaxies and the intergalactic medium, make cosmic ray driven galactic winds a particularly topical example.

Following theoretical work of Refs. 99 and 100, a quantitative model of a wind from the inner Milky Way was developed and shown to be in good agreement with soft x-ray and radio synchrotron observations.[101,102] These models show that thermal pressure alone is insufficient to unbind the gas, but gas pressure and an approximately equal amount of cosmic ray pressure acting together drive about $2M_\odot\,\mathrm{yr}^{-1}$ from the inner Galactic disk.

In principle, cosmic ray driving could be much larger, as in Ref. 103. It is suggested in Ref. 104 that the rate of star formation in galaxies, which is tied to the supernova rate and thus to the cosmic ray acceleration rate, may be inherently self-limiting because too large a cosmic ray pressure would drive the interstellar medium out of the galaxy.

Even when momentum input by cosmic rays is relatively unimportant, the cosmic ray heating predicted by self confinement theory can be significant. This form of heating in galaxy clusters was first studied in Ref. 105 and later taken up in Refs. 106–108. The thermal stability of cosmic ray heated gas in galaxy clusters was considered in Ref. 109.

Cosmic rays can also heat ionized interstellar gas, as proposed originally in Ref. 110 and recently evaluated as a supplemental energy source for the Milky Way's thick ionized gas layer.[111]

V. SUMMARY AND DISCUSSION

In this paper, I have provided a brief review of observed cosmic ray properties and how they lead to a picture in which cosmic rays are scattered by magnetic fluctuations frequently enough to confine them for millions of years and render them isotropic despite the small size and intermittent locations of the supernova remnants where they are most probably accelerated (Sec. II). I then laid out a model in which the cosmic rays trap themselves by amplifying hydromagnetic waves through a gyroresonant instability driven by super-Alfvénic cosmic ray streaming (Sec. III). In a steady state, dissipation balances cosmic ray excitation, and the cosmic rays transfer energy and momentum to the background. Self confinement seems to work for the bulk of the cosmic rays, but above $\sim$100 GeV damping overwhelms excitation and another source of fluctuations is needed to scatter the cosmic rays.

The near isotropy of all but the highest energy cosmic rays, which implies that their mean free path is short compared to typical interstellar length scales, leads naturally to a fluid description of cosmic rays. If self confinement holds, the cosmic rays are coupled to the background gas, depositing energy and momentum within it. As discussed in Sec. IV, the degree of coupling affects the strong, supernova driven shocks thought to be the source of cosmic ray acceleration, the stability of galactic disks and galaxy clusters to buoyancy instabilities, and gives rise to new instabilities. Momentum and energy deposition by cosmic rays drive galactic winds, and heat interstellar and intergalactic gas.

However, there is an alternative model, according to which cosmic rays are scattered by extrinsic turbulence, probably the short wavelength end of the interstellar MHD turbulent cascade. In this approach, energy flows from the waves to the cosmic rays rather than *vice versa*: cosmic rays undergo second order Fermi acceleration by the turbulence, which can be a significant energy sink for the turbulent cascade. In the presence of shear flows, cosmic rays are also subject to strong viscous heating or "shear acceleration."[112]

In some respects, these two pictures are complementary. Due to the decline in the growth rate of the streaming instability with cosmic ray energy, it is likely that extrinsic turbulence dominates the scattering for sufficiently energetic cosmic rays. Present estimates put the crossover from self confinement to scattering by extrinsic turbulence at about 100 GeV. Since most of the cosmic rays, and most of the cosmic ray energy, is below this transition, the overall flow of energy and momentum from the cosmic rays to the background should proceed according to the self confinement picture. However, this conclusion depends on the properties of the background medium, and especially on the properties of interstellar turbulence. As we discussed in Sec. IV, turbulent wandering of the interstellar magnetic fieldlines has been proposed as a damping mechanism for the cosmic ray streaming instability. The damping rate depends on the turbulent amplitude and on the spectrum, which are likely to vary throughout the interstellar medium. And, the wandering has not been accounted for in computing the growth rate of the streaming instability.

The nature of interstellar turbulence is also important for understanding how cosmic rays cross magnetic fieldlines. Galactic propagation codes typically define perpendicular and parallel spatial diffusion coefficients with respect to the *mean* magnetic field, with the understanding that perpendicular diffusion is a compound of both fieldline wandering and actual cross-field motion. The latter is most interesting in a turbulent or stochastic magnetic field, and requires some structure in the field on the scale of the particle gyroradius. Even the small cross field displacement associated with pitch angle scattering can nudge a particle onto a completely different magnetic flux bundle, increasing the rate of cross field transport dramatically. There has been progress in describing transport under particular conditions. But again, quantifying cross field transport requires a good understanding of interstellar magnetic turbulence on a small scale.

The prospects are good for making progress in understanding cosmic ray acceleration, propagation, and interaction with the background medium. Measurements of cosmic ray composition, the cosmic ray spectrum, and cosmic ray anisotropy are reaching greater precision and extending over greater energy ranges. Improved sensitivity and wavelength coverage are making it possible to observe cosmic rays in other galaxies. The propagation of energetic particles and their interaction with waves is being probed in laboratory plasmas; shocks can be studied in high energy density plasmas. Our understanding of magnetized turbulence in the interstellar medium is advancing. Numerical simulations of every aspect of the problem, from particle orbit theory to self consistent turbulent shock models, are increasingly powerful and accountable to laboratory data. All these developments make the plasma physics of cosmic rays ripe for future work.

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