Cosmic Rays and Particle Acceleration

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Astronomy 253: Plasma Astrophysics

April 14–16, 2014

These lecture notes are based off of P. Carlson (2012), Zweibel (2013), Kulsrud, and slides by P. Blasi and others. The derivations for first and second order Fermi acceleration follow *High Energy Astrophysics* by Longair (3rd ed). This book contains several very nicely written chapters on relativistic particle dynamics, cosmic rays, and particle acceleration.

Outline

- History and importance of cosmic rays
- Detecting cosmic rays
- Properties of cosmic rays
- Second order Fermi acceleration
- First order Fermi acceleration (diffusive shock acceleration)
- Ultra-high energy cosmic rays

Introduction

- Cosmic rays (CRs) are highly energetic particles that mostly originate outside of our solar system
- Cosmic rays are in rough energy equipartition with our galaxy's magnetic field, the cosmic microwave background, and starlight
- The most fundamental questions of cosmic ray research are:
    - What are the source regions of cosmic rays?
    - How are cosmic rays accelerated?
    - How do cosmic rays propagate in the galaxy?
- Particle astrophysicists have made progress on all of these questions but much work remains
- Galactic and extragalactic cosmic rays are not the only energetic particles that we care about: there are also solar energetic particles (SEPs)!

History of cosmic ray research

- Research question in early 1900s: what is the source of atmospheric ionization?
  - Experiments by Coulomb in 1785 showed that a charged metallic sphere left alone in air gradually loses its charge
- Cosmic rays were first discovered by Victor Hess in balloon experiments in 1912
  - The amount of atmospheric ionization *increased* with height
  - Origin of atmospheric ionization is extraterrestrial!
- Sea voyages by Clay (1927) and Millikan (1932) showed a dependence of cosmic ray flux on latitude
  - Modulation by Earth's magnetic field
  - Effect more pronounced for lower energy cosmic rays
  - Cosmic rays are (mostly) charged particles!
- More CRs came from the west than the east (late 1920s to 1930s)
  - Most CRs are positively charged!

Cosmic ray research led to the discoveries of several new particles

- Before particle accelerators, CRs were the best way to study high energy particle physics!
- Cloud chamber observations of CRs by Anderson led to the discovery of the positron (1932) and the muon (1936)
- Pions were discovered in CR observations in 1947
- The first CR antiproton was discovered in 1979
- These are secondaries resulting from collisions of primary cosmic rays with other nuclei

What effects do cosmic rays have on astrophysical plasmas?

- Vertical support of ISM in galaxies
- Ionization and heating of ISM through collisions
  - Allows weak ionization in molecular clouds, protoplanetary disks, and the cold neutral medium
  - Impacts chemistry in the ISM and molecular clouds
  - Low energy CRs ($\lesssim$ 10 MeV) are most responsible for this
- Probable driver of galactic winds
- Amplification of magnetic fields
  - Upstream and downstream of shocks
  - Cosmic ray driven dynamo
- Modification of astrophysical plasma processes
  - Shocks, dynamos, jets, reconnection

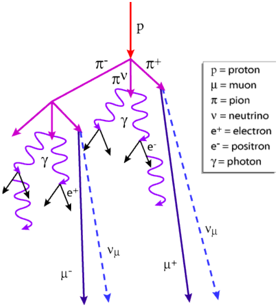
Why should humans care about cosmic rays?

- Contribution to atmospheric chemistry
  - Production of $^{14}\mathrm{C}$ in the atmosphere through the neutron capture reaction
    $$\mathrm{n} + {}^{14}\mathrm{N} \rightarrow {}^{14}\mathrm{C} + \mathrm{p} \tag{1}$$
  - Historical spikes of $^{14}\mathrm{C}$ production (e.g., 774–775 CE) possibly due to cosmic ray events
- Source of background radiation
  - Airline pilots have a higher risk of cataracts due to CRs
- CRs and SEPs are a health hazard for interplanetary space travel (in particular, outside of Earth's magnetosphere)
- Impact on Earth and space based electronics
  - Cosmic rays cause bit flips (e.g., error on Voyager 2)
  - Increases with altitude in atmosphere
  - Error correction schemes can mitigate these effects

Why should particle physicists care about cosmic rays?

- The maximum energy of cosmic rays is of order 10^{20} eV
  - Orders of magnitude greater energy than accessible by the Large Hadron Collider (LHC) at CERN!
  - Possible to investigate particle physics at otherwise inaccessible energies
- Higher energy cosmic rays induce particle showers in atmosphere
- Difficulties:
  - Lack of experimental control
  - Lack of cross-checks with experiment at these energies
  - Rarity of most energetic events

Primary cosmic rays collide with molecules in the atmosphere and yield secondary particles in an air shower



- Common products: pions, electrons, positrons, neutrons, kaons, muons, and neutrinos
- Particles produce Cherenkov radiation that is detectable

Particle profile: pions

- Pions are mesons: they consist of a quark and antiquark

$$\pi^+ : u\bar{d} \qquad \pi^0 : u\bar{u} \text{ or } d\bar{d} \qquad \pi^- : d\bar{u}$$

- Charged pions have a mass of 139.6 MeV/c^2. The most common decay routes are

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \tag{2}$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \tag{3}$$

  with a characteristic decay time of 26 ns

- Neutral pions have a mass of 135.0 MeV/c^2 and usually decay into two photons with a characteristic time of 8.4×10^{-17} s:

$$\pi^0 \rightarrow 2\gamma \tag{4}$$

- Gamma rays from pion decay are detectable by *Fermi*

Particle profile: muons

- Muons (μ^-, μ^+) are leptons with a mass of 105.7 MeV/c^2 (about 200 times the mass of an electron)
- Most naturally occuring muons are cosmic ray secondaries resulting from pion decay
- Muons have a mean lifetime of 2.2 μs
  - That's really long!
  - Time dilation allows muons to propagate longer distances in our frame before decaying
- The most common decay routes are

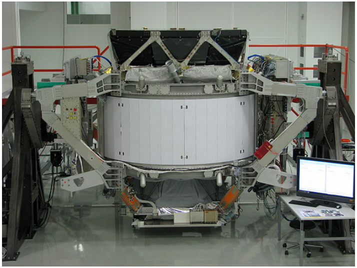
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \tag{5}$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \tag{6}$$

How are cosmic rays observed?

- Synchrotron radiation
- Gamma rays (pion decay bump)
- Cloud chambers and bubble chambers
    - Important historically; mostly obsolete
- Magnetic spectrometers
    - High precision measurements of bending of cosmic ray paths by an applied magnetic field
    - Useful at relatively low energies
- Cherenkov radiation
    - Particles traveling faster than the speed of light in a medium

Alpha Magnetic Spectrometer



- A magnetic spectrometer[1] on the *International Space Station*
- Above atmosphere so it measures primary cosmic ray population
- Measuring electron-to-positron ratio
  - Provides limits on annihilation of dark matter particles
- Required a special act of Congress to get it launched!

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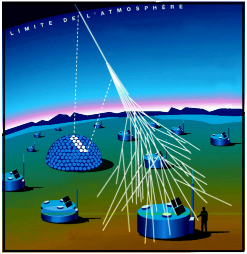
[1] The first rule of tautology club is the first rule of tautology club.

Pierre Auger Observatory



- Observes air showers of secondary cosmic ray particles
- Rate of ultra-high energy cosmic rays is ~ 1 km^{-2} century^{-1}
- Effective area is ~ 3000 km^2
- Fluorescence detectors to observe air showers in atmosphere
- Cherenkov detectors to detect secondary particles on ground
- Combination of both methods reduces systematic errors that resulted during prior work
- A key result: anisotropy of UHECRs (more later)

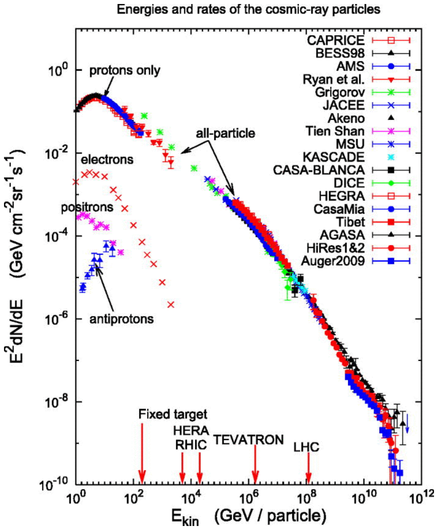
What are the properties of cosmic rays?

- Energy spectrum
- Abundances
- Confinement/lifetimes
- Isotropy/anisotropy

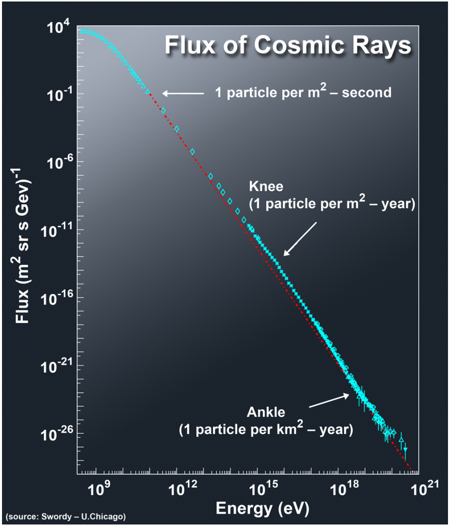
Cosmic ray research is a great way to get practice with rarely used SI prefixes!

Prefix	Symbol	1000^m	10^n	Decimal	English word		Since[n 1]
					short scale	long scale	
yotta	Y	1000^8	10^{24}	1 000 000 000 000 000 000 000 000	septillion	quadrillion	1991
zetta	Z	1000^7	10^{21}	1 000 000 000 000 000 000 000	sextillion	thousand trillion	1991
exa	E	1000^6	10^{18}	1 000 000 000 000 000 000	quintillion	trillion	1975
peta	P	1000^5	10^{15}	1 000 000 000 000 000	quadrillion	thousand billion	1975
tera	T	1000^4	10^{12}	1 000 000 000 000	trillion	billion	1960
giga	G	1000^3	10^9	1 000 000 000	billion	thousand million	1960
mega	M	1000^2	10^6	1 000 000	million		1960
kilo	k	1000^1	10^3	1 000	thousand		1795

Energy spectrum of cosmic rays



Energy spectrum of cosmic rays



(source: Swordy – U.Chicago)

- *Knee* around 3×10^{15} eV
- *Ankle* around a few $\times$ 10^{18} eV

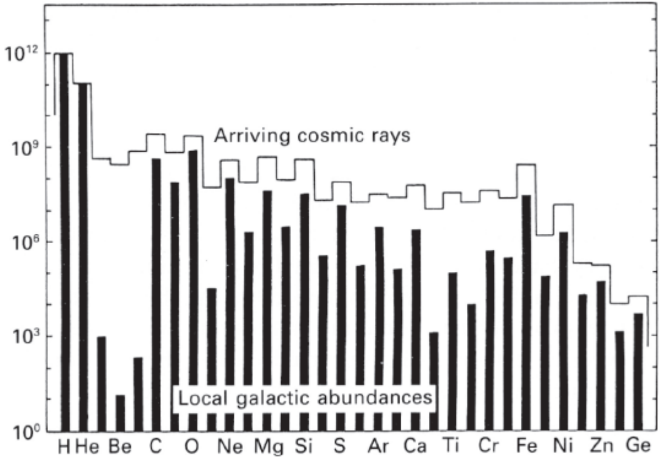
Energy spectrum of cosmic rays

- Flux of lowest energy cosmic rays is uncertain due to heliospheric modulation
  - Solar energetic particles present at lower energies ($\sim$keV to $\sim$100 MeV)
- From $\sim 10^9$ to $\sim 10^{15}$ eV the power law index is $\approx$2.7
  - This part of the spectrum contains most of the cosmic ray energy density
- Above the knee the index steepens to $\approx$3.0
- The spectrum starts to flatten again around the ankle at a few $\times\ 10^{18}$ eV

Why do the knee and ankle exist in the cosmic ray power spectrum?

- Changes in the spectral index may indicate a transition in the acceleration or confinement mechanism and/or composition
- The knee is postulated to be an upper limit associated with the acceleration mechanism for galactic cosmic rays
  - Can diffusive shock acceleration in supernova remnants reach this energy?
  - Does the knee have anything to do with particle transport or escape?
- Cosmic rays above the ankle are extragalactic in origin
  - Gyroradius is comparable to size of galaxy
- Neither the knee nor the ankle is well-understood
- Question: how could we determine if cosmic rays between the knee and ankle are galactic or extragalactic?

Abundances of cosmic rays



The cosmic abundances of the elements in the cosmic rays (solid line) compared with the Solar System abundances (solid histogram). The data have been normalised to a relative abundance of hydrogen of 10^{12} (Lund, 1984).

Abundances of cosmic rays

- Relative abundances are more or less representative of interstellar plasmas
  - H and He are somewhat underabundant
- $\sim$89% are protons
- $\sim$10% are α particles
- Overabundance of $^3\mathrm{He}$, Li, Be, and B (by 5–7 orders of magnitude at $\sim$1 GeV)
- 1–2% are electrons
  - Steeper slope because of radiative losses
  - Very low density of cosmic rays $\rightarrow$ maintaining quasineutrality is not a problem
- Very small fraction of CRs are positrons or antiprotons
- No antihelium nuclei yet discovered in cosmic rays

Are Coulomb collisions significant?

- Recall: Coulomb collisions occur when a particle interacts with another particle via electric fields
- The Coulomb cross section of a 1 GeV particle is 10^{-30} cm^2: tiny!
- For 1 GeV cosmic rays propagating in the ISM ($n \sim 1$ cm^{-3}), the mean Coulomb collision rate is

  $$n\sigma v \sim 10^{-19.5} \text{ s}^{-1} \tag{7}$$

  This corresponds to a 1% chance of a Coulomb collision during a Hubble time!
- Coulomb collisions can therefore be neglected completely

Spallation reactions provide limits on cosmic ray lifetimes

- Species such as $^3\mathrm{He}$, Li, Be, and B are very overabundant in galactic cosmic rays
- Spallation occurs when C, N, O, Fe nuclei impact interstellar hydrogen
- The larger nuclei are broken up into smaller nuclei
- The abundance enhancements of the lighter elements show that spallation reactions are somewhat important
  - Must have passed through $\gtrsim 3\ \mathrm{g\,cm^{-2}}$ of the ISM
- Heavier elements such as Fe are only mildly depleted
  - Cannot have passed through more than $\sim 5\ \mathrm{g\,cm^{-2}}$ of material
- This corresponds to a cosmic ray lifetime of 3 Myr in the disk (or significantly longer in the halo)
- Radioactive isotopes provide an additional diagnostic
  - Example: $^{10}\mathrm{Be}$ has a half-life of 1.5 Myr

Cosmic rays are effectively confined if the Larmor radius is much smaller than the system size

- Relativistic momentum: $\mathbf{p} = \gamma m \mathbf{v}$
- The relativistic Larmor radius is

$$r_L = \frac{p_\perp}{|q|B} = \frac{\gamma m v}{ZeB} \tag{8}$$

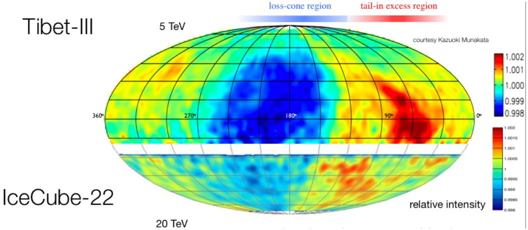
This can be written for a proton as

$$r_L = \frac{pc/\mathrm{eV}}{300(B/\mathrm{G})}\ \mathrm{cm} \tag{9}$$

How effectively are cosmic rays confined in different systems?

- Calculate the particle energy associated with a gyroradius equal to the characteristic length scale
- Heliosphere: $L \sim 100$ AU, $B \sim 10\ \mu$G $\Rightarrow \mathcal{E}_L \sim 4 \times 10^{12}$ eV
    - Low energy cosmic rays are modulated by heliospheric magnetic fields
- ISM: $L \sim 100$ pc, $B \sim 5\ \mu$G $\Rightarrow \mathcal{E}_L \sim 4 \times 10^{17}$ eV
    - The highest energy cosmic rays are barely deflected by the magnetic field of the Milky Way

Isotropy of cosmic rays below the knee



- Below $\sim 10^{14}$ eV, cosmic rays are highly isotropic
- Cosmic rays propagate along field lines in galaxy
- Propagation and confinement make it difficult to determine source regions
- Scattering and diffusion play an important role
- Weak anisotropy (above) is not well understood

What properties of cosmic rays must an acceleration mechanism explain?

- A power law energy spectrum for particles of all types:

  $$\mathrm{d}N(E) \propto E^{-x}\mathrm{d}E \tag{10}$$

  The exponent x is usually in the range of $\sim$2.2–3.0.
- The acceleration of cosmic rays to maximum observed energies
  - For galactic cosmic rays, energies up to the knee: $\sim 10^{15}$ eV
  - For extragalactic cosmic rays, energies beyond the ankle: $\sim 10^{20}$ eV
- Elemental abundances of cosmic rays similar to interstellar/circumstellar abundances

General principles of acceleration

- The equation of motion for a charged particle is

$$\frac{\mathrm{d}}{\mathrm{d}t}(\gamma m\mathbf{v}) = q\left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right) \tag{11}$$

  where $\gamma \equiv \frac{1}{\sqrt{1 - v^2/c^2}}$ is the Lorentz factor and q, m, and $\mathbf{v}$ are the charge, mass, and velocity of the particle
- Magnetic fields themselves do no work and cannot be directly responsible for acceleration, but changing magnetic fields lead to an inductive electric field

Direct acceleration by a static electric field

- Direct acceleration requires a nonzero average electric field:

$$\langle \mathbf{E} \rangle \neq 0 \tag{12}$$

- Electric fields that develop due to charge separation will quickly short themselves out by motion of free charges
- Thus, we'd normally expect that direct acceleration will not suffice to describe observations of CRs
- Important exception: magnetic reconnection
    - Development of strong localized **E**

Second order Fermi acceleration[2]

- Prior to 1949, suggested sources of cosmic rays included magnetically variable stars and supernovae
  - Details of proposed mechanisms were lacking
  - Difficulty in explaining the observed cosmic ray spectrum
- Fermi (1949) proposed a model for acceleration in which particles can statistically gain energy through collisions with interstellar clouds
  - Original model led to second order acceleration: $\frac{\Delta \mathcal{E}}{\mathcal{E}} \propto \left(\frac{V}{c}\right)^2$
  - By assuming a characteristic escape time, τ_{esc}, this results in a power law distribution of particle energies

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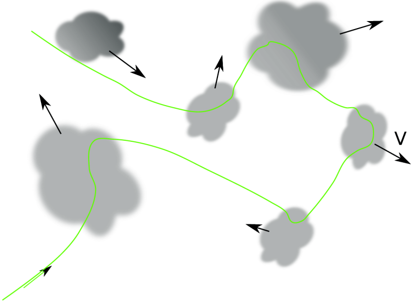
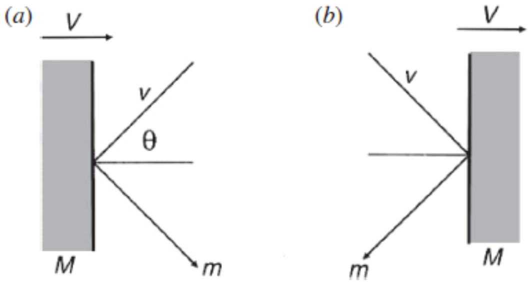
[2] Following Longair's textbook

Acceleration occurs by particles having random collisions with interstellar clouds with characteristic velocity V



- Reflection of particles due to magnetic mirror effects

Geometry of collisions



- Energy is gained during a head-on collision (a) and lost during a trailing collision (b)
- Parameters:
  - V: characteristic cloud velocity in observer's frame
  - v: velocity of particle
  - θ: angle of incidence
  - m: particle mass ($\ll M \equiv$ cloud mass)

Key point: head-on collisions are more likely than trailing collisions

- The probability of a head-on collision is proportional to

$$v + V\cos\theta \tag{13}$$

- The probability of a trailing collision is proportional to

$$v - V\cos\theta \tag{14}$$

- Same principle as driving on a highway: there will be more cars passing you by from oncoming traffic than traffic going in the same direction
  - Further generalizable to 3D bumper cars piloted by space wombats

It is necessary to do a fully relativistic analysis

- The particle energy $\mathcal{E}$ in the cloud's (center of momentum) reference frame is

  $$\mathcal{E}' = \gamma_V (\mathcal{E} + Vp \cos\theta) \tag{15}$$

  where p is the particle's momentum, θ is the angle of incidence, and the Lorentz factor is

  $$\gamma_V = \left(1 - \frac{V^2}{c^2}\right)^{-1/2} \tag{16}$$

Reversing the x component of momentum in cloud frame

- The x component of momentum in this frame is

$$p'_x = p' \cos\theta' = \gamma v \left(p \cos\theta + \frac{V\mathcal{E}}{c^2} \right) \tag{17}$$

- During the collision:
  - The particle's energy is conserved
  - The x component of the particle's momentum is reversed

$$p'_x \to -p'_x \tag{18}$$

- Then transform back into the observer's frame:

$$\mathcal{E}'' = \gamma_V \left(\mathcal{E}' + V p'_x \right) \tag{19}$$

Finding the change in energy for a collision

- Combinging Eqs. 15, 17, & 19 yields an expression for the particle energy in the observer's frame:

$$\mathcal{E}'' = \gamma^2 \mathcal{E} \left[1 + \frac{2Vv\cos\theta}{c^2} + \left(\frac{V}{c}\right)^2 \right] \tag{20}$$

- Then expand to second order in V/c and solve for $\Delta\mathcal{E}$

$$\mathcal{E}'' - \mathcal{E} \equiv \Delta\mathcal{E} = \mathcal{E} \left[\frac{2Vv\cos\theta}{c^2} + 2\left(\frac{V}{c}\right)^2 \right] \tag{21}$$

We still need to average over the angle of incidence, θ

- Assume that particle is randomly scattered in pitch angle
    - Distribution of angles is random
- Simplify by assuming that the particles are relativistic: $v \approx c$
- Use that the probability of an angle between θ and $\theta + \mathrm{d}\theta$ is proportional to $\sin\theta\,\mathrm{d}\theta$
    - Analogous to the reason why we see more galaxies edge-on than face-on
- Average over the range 0 to π
- The average of the θ-dependent term in Eq. 21 becomes

$$\left\langle \frac{2V\cos\theta}{c} \right\rangle = \left(\frac{2V}{c}\right) \frac{\int_{-1}^{1} X\left[1 + \frac{V}{c}X\right]\,\mathrm{d}X}{\int_{-1}^{1}\left[1 + \frac{V}{c}X\right]\,\mathrm{d}X} = \frac{2}{3}\left(\frac{V}{c}\right)^2 \quad (22)$$

where we use the substitution $X \equiv \cos\theta$

The average increase of energy per collision is only *second order* in V/c

- The full average over theta finally yields and expression for the average increase in energy during a collision

$$\left\langle \frac{\Delta\mathcal{E}}{\mathcal{E}} \right\rangle = \frac{8}{c}\left(\frac{V}{c}\right)^2 \tag{23}$$

- The same fractional increase occurs during every collision
- Define L as mean free path and ϕ as pitch angle
- The time between collisions $\sim L/c\cos\phi$, which can be averaged to $2L/c$
- The average rate of energy increase is

$$\frac{\mathrm{d}\mathcal{E}}{\mathrm{d}t} = \frac{4}{3}\left(\frac{V^2}{cL}\mathcal{E}\right) = \alpha\mathcal{E} \tag{24}$$

What is the spectrum of the accelerated particles?

- The diffusion-loss equation provides a convenient way of calculating the spectrum

$$\frac{\mathrm{d}N}{\mathrm{d}t} = D\nabla^2 N + \frac{\partial}{\partial \mathcal{E}}[b(\mathcal{E})N(\mathcal{E})] - \frac{N}{\tau_{esc}} + Q(\mathcal{E}) \tag{25}$$

  - $N(\mathcal{E})$ is the number of particles between $\mathcal{E}$ and $\mathcal{E} + \Delta\mathcal{E}$
  - $D\nabla^2 n$ is the diffusive term (which we ignore)
  - $b(\mathcal{E}) = -\mathrm{d}\mathcal{E}/\mathrm{d}t$ is the energy loss term
  - $Q(\mathcal{E})$ represents sources (which we ignore)
  - τ_{esc} is the escape time

Deriving the energy spectrum

- If we assume a steady state and use our expression for a gain in energy, $b(\mathcal{E}) = -\alpha\mathcal{E}$, then this equation becomes

$$-\frac{\mathrm{d}}{\mathrm{d}\mathcal{E}}[\alpha\mathcal{E}N(\mathcal{E})] - \frac{N(\mathcal{E})}{\tau_{esc}} = 0 \tag{26}$$

- Differentiating then yields

$$\frac{\mathrm{d}N(\mathcal{E})}{\mathrm{d}\mathcal{E}} = -\left(1 + \frac{1}{\alpha\tau_{esc}}\right)\frac{N(\mathcal{E})}{\mathcal{E}} \tag{27}$$

- The solution is then

$$N(\mathcal{E}) \propto \mathcal{E}^{-x} \tag{28}$$

  where $x \equiv 1 + (\alpha\tau_{esc})^{-1}$
- This is a power law! But α and τ_{esc} are model-dependent.

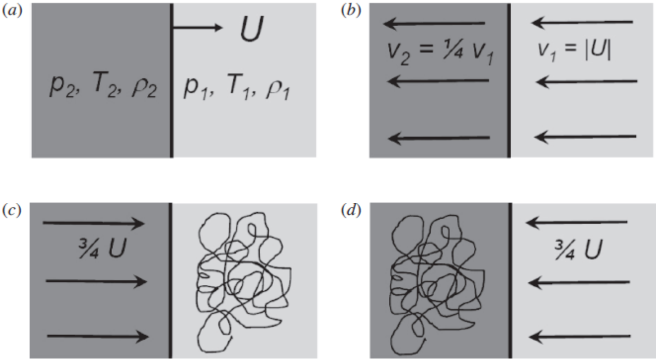
What are the problems with second order Fermi acceleration?

- The random velocities of clouds are relatively small: $V/c \lesssim 10^{-4}$
- For a CR mean free path of $\sim$0.1 pc, collisions would likely occur only a few times per year
- Very little chance of a particle gaining significant energy!
- This theory does not include energy losses that compete with energy gains (e.g., ionization)
- The theory does not predict the power law exponent
  - Why are the spectra of energetic particles so similar?
- Biggest problem: energy gains are second order: $\mathcal{O}(V^2/c^2)$
  - Some collisions result in energy losses!

Setting the stage for first order Fermi acceleration

- What if we could find a similar mechanism in which every interaction resulted in an increase in energy?
  - This would be a first order process! $\mathcal{O}(V/c)$
- The occurs during diffusive shock acceleration if particles can bounce back and forth in the upstream and downstream regions and always approach plasma moving toward them
  - Not *quite* the same idea as improving gas mileage by making all roads downhill
- An energetic particle propagating through the shock front would barely notice it if the particle's gyroradius is much larger than the shock thickness
- The velocity becomes isotropized due to streaming instabilities and turbulent motions
- Define U as the shock velocity

In the pre-shock and post-shock reference frames



- (a) Observer's frame, (b) reference frame of shock, (c) upstream frame, (d) downstream frame
- When crossing the shock from either side, the particle sees plasma moving toward it at a velocity of $V \equiv \frac{3}{4}U$

Let's look at Fermi acceleration more generally

- Define $\mathcal{E} = \beta \mathcal{E}_0$ as the average energy of the particle after a collision
- Define P as the probability that the particle remains in the acceleration region after a collision
- After k collisions there are $N = N_0 P^k$ particles with energies $\mathcal{E} = \mathcal{E}_0 \beta^k$

Relating the spectrum to energy gain and loss probability

- Eliminating k yields

$$\begin{aligned} \frac{\ln(N/N_0)}{\ln(\mathcal{E}/\mathcal{E}_0)} &= \frac{\ln P}{\ln \beta} && (29) \\ \Rightarrow \frac{N}{N_0} &= \left(\frac{\mathcal{E}}{\mathcal{E}_0}\right)^{\ln P/\ln \beta} && (30) \end{aligned}$$

- The power spectrum is then

$$N(\mathcal{E})\,\mathrm{d}\mathcal{E} \propto \mathcal{E}^{-1+(\ln P/\ln \beta)}\,\mathrm{d}\mathcal{E} \qquad (31)$$

- From second order Fermi acceleration, this means that

$$\frac{\ln P}{\ln \beta} \equiv -(\alpha\tau_{esc})^{-1} \qquad (32)$$

Let's evaluate the fractional increase in energy for one acceleration cycle

- A particle with energy $\mathcal{E}$ on the upstream side sees plasma approaching it at a velocity V from the downstream side
- The particle's energy in the downstream frame is

$$\mathcal{E}' = \gamma_V(\mathcal{E} + p_x V) \tag{33}$$

- Assume shock is non-relativistic so $\gamma_V = 1$
- The particles are relativistic so $p_x = \frac{E}{c}\cos\theta$ and therefore

$$\Delta\mathcal{E} = pV\cos\theta \tag{34}$$

$$\frac{\Delta\mathcal{E}}{\mathcal{E}} = \frac{V}{c}\cos\theta \tag{35}$$

where we use that $\mathcal{E} = pc$

What is the probability of an angle θ?

- The probability that a particle will cross the shock with an angle of incidence between θ and $\theta + \mathrm{d}\theta$ is proportional to $\sin\theta \, \mathrm{d}\theta$
- The rate at which they approach the shock front is proportional to $v_x = c\cos\theta$
- For $\theta \in [0, \pi/2]$, the probability function for θ is

$$p(\theta) = 2\sin\theta \, \cos\theta \, \mathrm{d}\theta \tag{36}$$

- Eq. 35 then averages to

$$\begin{aligned} \left\langle \frac{\Delta\mathcal{E}}{\mathcal{E}} \right\rangle &= \frac{V}{c}\int_0^{\pi/2} 2\cos^2\theta\sin\theta \, \mathrm{d}\theta \\ &= \frac{2}{3}\frac{V}{c} \end{aligned} \tag{37}$$

which gives the energy increase for one shock crossing

Because plasma appears to be moving towards particles crossing the shock front at equal velocities from each side, the energy gain is symmetric

- The fractional increase in energy after a round trip is given by

$$\left\langle \frac{\Delta\mathcal{E}}{\mathcal{E}} \right\rangle = \frac{4}{3}\frac{V}{c} \tag{38}$$

- This means that the energy change after a round trip is given by

$$\beta \equiv \frac{\mathcal{E}}{\mathcal{E}_0} = 1 + \frac{4}{3}\frac{V}{c} \tag{39}$$

- First order Fermi acceleration is first order in $\frac{V}{c}$!

How do we estimate the escape probability per cycle?

- The rate of particles crossing the shock from either direction is $\frac{1}{4}nc$, where n is the number density of energetic particles and we average over velocities/angles
- Upstream particles are swept into the shock, so few losses
- Particles removed from downstream region at a rate of $nV = \frac{1}{4}nU$
- The fraction of particles lost is then $\frac{1}{4}nU/\frac{1}{4}nU = U/c$ so that the fraction of particles remaining after one cycle is

$$P = 1 - \frac{U}{c} \tag{40}$$

Since $U \ll c$, few particles are lost per cycle

What is the power law exponent?

- We then have

$$\begin{aligned} \ln P &= \ln\left(1 - \frac{U}{c}\right) = -\frac{U}{c} && (41) \\ \ln\beta &= \ln\left(1 + \frac{4}{3}\frac{V}{c}\right) \simeq \frac{4}{3}\frac{V}{c} = \frac{U}{c} && (42) \end{aligned}$$

  so that

$$\frac{\ln P}{\ln\beta} = -1 \qquad (43)$$

- The energy spectrum is then

$$N(\mathcal{E})\,\mathrm{d}\mathcal{E} \propto \mathcal{E}^{-2}\,\mathrm{d}\mathcal{E} \qquad (44)$$

- This derivation predicts a value of the power law exponent which is not *too* different from the observed value of ∼2.7 for galactic cosmic rays

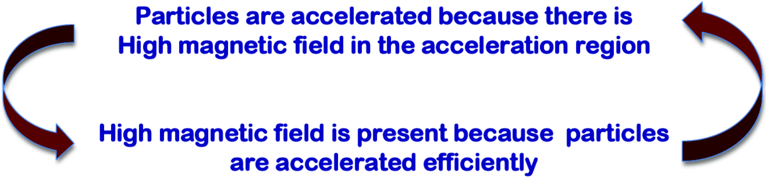
First order Fermi Acceleration

- This model provides an efficient method for accelerating particles in supernova remnant shock waves
- Requires that velocity vectors are randomized upstream and downstream of the shock
    - Scattering of CRs by Alfvén waves, etc.
- Requires prior injection of superthermal seed particles
- Energy losses are ignored
- This model neglects detailed physics of the magnetic field
- Key paper: Bell (1978). See also Longair book.

What is the maximum attainable energy by this mechanism?

- The magnetic field must be able to confine energetic particles
- For interstellar magnetic field strengths $\sim 1\mu$G, the proton Larmor radius is ~ 1 pc
- Supernova remnants could then not confine particles with energies $\gtrsim 10^{14}$ eV
- But what if there are mechanisms to amplify the magnetic field?

Magnetic perturbations can be amplified by super-Alfvénic streaming of cosmic rays



Particles are accelerated because there is High magnetic field in the acceleration region

High magnetic field is present because particles are accelerated efficiently

Magnetic field amplification by cosmic rays

- Nature of instabilities (e.g., Zweibel 1978; Bell 1978, 2004)
  - Upstream plasma responds to cosmic ray current with return currents to compensate for positive charge
  - The induced perturbations grow
- Key questions about these instabilities:
  - What is the nonlinear evolution and saturation of these instabilities?
  - How do cosmic rays diffuse?
- Can explain acceleration to 10^{17}–10^{18} eV in supernova remnant shock waves, but not to 10^{20} eV
- If we had more time, we could have an entire class on these topics!

Observation of the pion decay bump in a supernova remnant by *Fermi* (Ackermann et al. 2013)

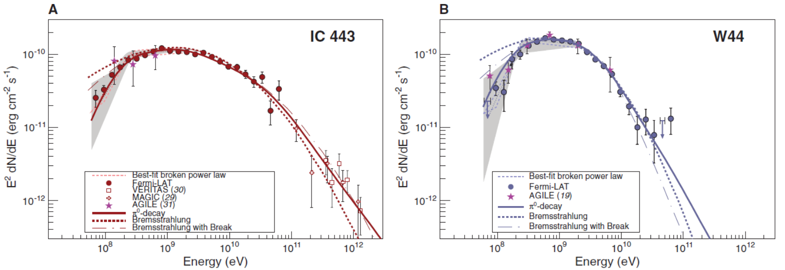


Fig. 2. (**A** and **B**) Gamma-ray spectra of IC 443 (A) and W44 (B) as measured with the Fermi LAT. Color-shaded areas bound by dashed lines denote the best-fit broadband smooth broken power law (60 MeV to 2 GeV); gray-shaded bands show systematic errors below 2 GeV due mainly to imperfect modeling of the galactic diffuse emission. At the high-energy end, TeV spectral data points for IC 443 from MAGIC (*29*) and VERITAS (*30*) are shown. Solid lines denote the best-fit pion-decay gamma-ray spectra, dashed lines denote the best-fit bremsstrahlung spectra, and dash-dotted lines denote the best-fit bremsstrahlung spectra when including an ad hoc low-energy break at 300 MeV c^{-1} in the electron spectrum. These fits were done to the Fermi LAT data alone (not taking the TeV data points into account). Magenta stars denote measurements from the AGILE satellite for these two SNRs, taken from (*31*) and (*19*), respectively.

- 67.5 MeV in rest frame of π^0
- Detection difficult because energetic electrons also emit gamma rays through bremsstrahlung and inverse Compton scattering

Open questions on galactic cosmic rays

- Why does the energy spectrum change its slope at $\sim 10^{15}$ eV?
- How are cosmic rays accelerated to $\sim 10^{17}$–10^{18} eV?
- Are cosmic rays between the knee and ankle: galactic, extragalactic, or a combination?
- What is the nature of cosmic ray diffusion and transport in galactic magnetic fields?
- What is the nature of instabilities that connect the magnetic field and cosmic ray populations?
    - Especially the nonlinear evolution

THE ORIGIN OF ULTRA-HIGH-ENERGY COSMIC RAYS

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1. WHY BOTHER WITH ULTRA-HIGH-ENERGY COSMIC RAYS?

Ultra-high energy cosmic rays

- Major problem: how are particles accelerated to 10^{20} eV?
  - The energy of a fastball in a single particle!
- Orders of magnitude more energy than any particle accelerator humans have constructed!
  - Venturing into regions of particle physics parameter space that cannot be cross-checked in the laboratory
- Cannot be confined in the Milky Way
  - Extragalactic source
- What is the nature of the primary particles?
- State-of-the-art observations are from the Pierre Auger Observatory

Possible sources of UHECRs (‘Hillas plot’ from Kotera & Olinto 2011)

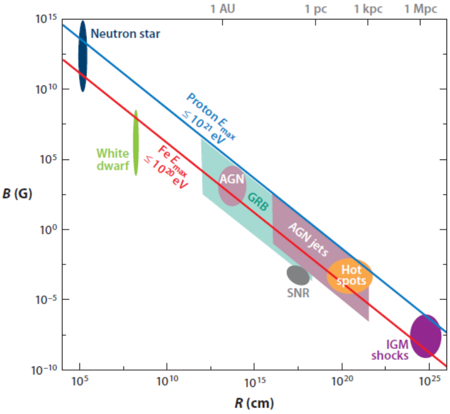


Figure 8

Updated Hillas (1984) diagram. Above the dark blue lines, protons can be confined to energies above $E_{\max} = 10^{21}$ eV. Above the red line, iron nuclei can be confined to energies above $E_{\max} = 10^{20}$ eV. The most powerful candidate sources are shown with the uncertainties in their parameters. Abbreviations: AGN, active galactic nuclei; GRB, gamma-ray burst; IGM, intergalactic medium; SNR, supernova remnant.

- UHECRs of these types can be confined above these lines

Possible sources of UHECRs

- Mechanisms include
    - Fermi acceleration at shock waves (mildly relativistic shocks?)
    - Unipolar inductors (neutron stars?)
- Possible source regions include
    - Gravitational accretion shocks (around clusters of galaxies?)
    - Active galactic nuclei (jets? central region?)
    - Gamma ray bursts (highly magnetized shocks?)
    - Neutron stars (magnetars?)
- Much work needs to be done both theoretically and observationally

Intergalactic propagation of cosmic rays

- At energies above the knee, pair production becomes possible through interaction with cosmic microwave background (CMB) photons

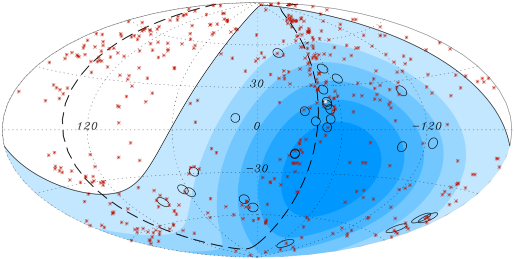
$$\mathrm{p} + \gamma_{CMB} \rightarrow \mathrm{p} + \mathrm{e}^{+} + \mathrm{e}^{-} \tag{45}$$

  - Fraction of energy lost in each interaction is small so effective interaction distance remains large: $\sim$ 600 Mpc
- At energies above $\sim 10^{20}$, pion production becomes possible

$$\mathrm{p} + \gamma_{CMB} \rightarrow \mathrm{p} + \pi^{0} \tag{46}$$
$$\mathrm{p} + \gamma_{CMB} \rightarrow \mathrm{n} + \pi^{+} \tag{47}$$

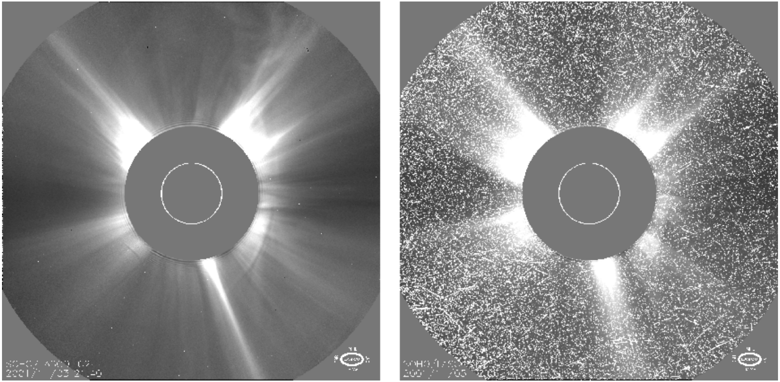
- More energy is lost so the interaction distance is much shorter: 50–100 Mpc (GZK limit)
- UHECRs are consequently thought to originate closer than this distance
- Are there UHECRs above this limit from further away?

Anisotropy of ultra-high energy cosmic rays



- The Pierre Auger Observatory has measured anisotropy of UHECRs (above 5×10^{19} eV)
  - Circles indicate UHECRs; red crosses indicate nearby AGN
- Arrival directions correlated with AGN within ∼75 Mpc
- Identification is tentative
  - Could this actually be the last scattering surface instead of the source?

Solar Energetic Particles (SEPs)

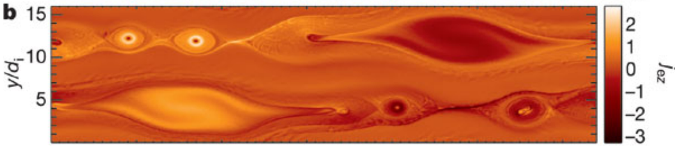


- Before and after a solar eruption that led to an SEP event

Solar Energetic Particles (SEPs)

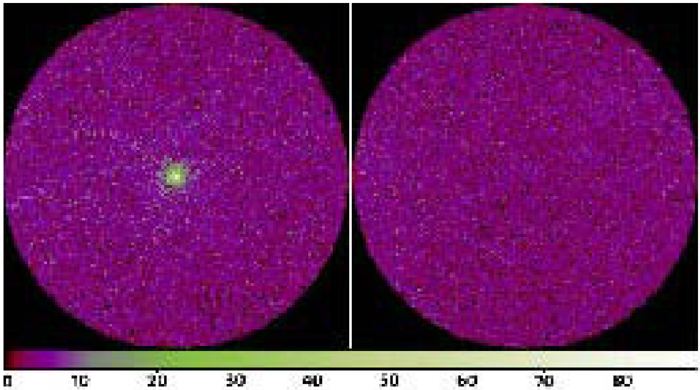
- Two sources that result from solar flares, coronal mass ejections, and other solar eruptions
  - Reconnection (impulsive events)
  - Shocks (gradual events)
- Energies up to $\sim$100 MeV or $\sim$1 GeV
- SEPs propagate mostly along field lines
  - We'll observe an SEP event if there are magnetic field lines attaching the source region to us
  - Occasional events are observed at spacecraft 180° apart
- One of the major components of space weather
- Observations of solar flares suggest that $\sim$all of the electrons in the source region are accelerated

Acceleration due to contracting islands during reconnection



- ‘Magnetic islands’ often form during reconnection
  - ‘Flux ropes’ in 3D
- Drake *et al.* have suggested that contraction of these islands leads to Fermi acceleration of confined particles
- Applied to solar flares, boundary of heliosphere, etc.
- Alternative to direct acceleration by the electric field
- 3D structure is vital to how this process works

The Sun emits gamma rays!



- Two source regions:
  - Compact source: cosmic ray cascades in photosphere
  - Extended source: inverse Compton scattering in corona during which cosmic rays give a kick to photons

Summary

- Cosmic rays are important astrophysically, terrestrially, and in particle physics
  - We can actually detect stuff besides photons!
- The most important observed/inferred properties of cosmic rays include their energy spectrum, abundances, confinement/lifetimes, and isotropy
- Diffusive shock acceleration in supernova remnants is the most promising mechanism for cosmic ray acceleration to energies up to the knee ($\lesssim 10^{15}$ eV)
- Cosmic-ray driven instabilities amplify the magnetic field surrounding shocks in supernova remnants
  - Improves confinement; allows acceleration to higher energies
- Summary of UHECRs: we don't know their composition, where they come from, or how they were accelerated