Particle Acceleration I: Astrophysical Mechanisms

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• Introduction

• Acceleration mechanisms
  – Changing Magnetic Fields
  – Mirror Effect
  – 2^{nd} Order Fermi Acceleration (turbulence)
  – Diffusive Shock Acceleration (1^{st} Order Fermi)
  – Acceleration in Reconnection zones

• Astrophysical Sites
High energy charged particles reaching the Earth’s atmosphere:

- electrons $\sim 1\%$
- protons $\sim 89\%$
- heavier nuclei, mainly helium $\sim 10\%$
- very few: antiparticles, muons, pions, kaons (from interactions of CRs with the interstellar gas)
COSMIC RAY SPECTRUM

\[ N(E) \propto E^{-\gamma} \]

- \( \gamma = 2.7 \) for \( 10^9 \text{eV} < E < E_{knee} \),
- \( \gamma = 3.0 \) for \( E_{knee} < E < E_{ankle} \),
- \( \gamma = 2.7 \) for \( E_{ankle} < E < E_{GZK} \)
COSMIC RAY SPECTRUM

- **knee:**
  particles with $E > 10^{15}$ eV start to leak from the galaxy, maximum from supernova explosions near $10^{15}$ eV

- **ankle:**
  extragalactic particles

- **GZK-cut off** at
  $\approx 6 \cdot 10^{19}$ GeV
CR – Magnetic Fields

Charged particles – circular orbits in Magnetic Field (MF):

\[ m \frac{dv}{dt} = qv \times B \]

**gyro-radius:**

\[ r_g = \frac{p}{qB} = \frac{\gamma m_0 v}{ZeB} \]

- **CRs with energies** \(< 10^{15} \text{ eV}$$**: sky distribution **ISOTROPIC**

- **Higher energy CRs:**

  are not as much deflected: **ANISOTROPIC**

  **Example:**

  \[ E = 10^{19} \text{ eV} \]
  \[ B = 2 \mu \text{G} \]

  \[ r_g = 10 \text{ kpc} \]

  no correlation with galactic plane:

  extragalactic origin
COSMIC RAY SOURCES

Hillas diagram. 1984

For particle to be confined within accelerating source:

\[ E_{\text{max}} \approx p_{\text{max}} \leq eBR \]

Gyro-radius < source size

\[ r_g < L \]

\[ E_{\text{max}} = BL \]

\( E_{\text{max}} \): Maximum energy that can be extracted from the source for acceleration
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• Astrophysical Sites
Electromagnetic Acceleration

• Time dependent MFs:
  Compact sources with large scale magnetic fields

solar sunspots  pulsars
Electromagnetic Acceleration

Faraday's law

\[ \nabla \times \mathbf{E} = -\dot{\mathbf{B}} \]

decaying magnetic field \( \Rightarrow \) electric field \( \Rightarrow \) acceleration

- magnetic flux: \( \Phi = B \cdot A = B\pi R^2 \)
- change of the flux \( \Rightarrow \) potential:

\[ U = \oint \mathbf{E} \cdot \mathbf{ds} = -\dot{\Phi} = -\dot{B}\pi R^2 \]

Cyclotron mechanism

Energy gain

\[ \Delta E = eU = e\pi R^2 \dot{B} \]

from one gyration

Kaiser courtesy
Electromagnetic Acceleration

Example: Merging Sunspots

- flux tube radius $R \approx 10^4 \text{km}$
- magnetic field $B \approx 2000 \text{ G}$
- merging in 1 day, $\dot{B} = 2000 \text{ G/day}$

$\Rightarrow E = 0.73 \text{ GeV}$
CRs from the Sun

Power law spectrum at high energies

Other mechanisms can be occurring:

- Diffusive shock acceleration
- Magnetic Reconnection
particles entering regions of higher magnetic field strength are reflected backwards

- charged particles follow cyclotron orbits
  \[
  \text{gyro-radius: } r_g = p_\perp / qB
  \]

stronger magnetic field
  ⇒ smaller gyro-radius, increased perpendicular velocity \( v_\perp \)
  ⇒ decrease of parallel velocity \( v_\parallel \) (energy conservation)
  ⇒ \( v_\parallel \) → 0, then reflection

The magnetic flux
\[
\Phi = B \cdot \pi r_g^2 \propto \frac{v_\perp^2}{B}
\]
through the particles' cyclotron circle is constant.
Fermi (1949): could CRs be produced via random scattering with magnetized interstellar clouds?
FERMI ACCELERATION

Frequency of head-on collisions > frequency of catch-up collisions

net energy gain by particles
FERMI ACCELERATION

Head-on collision:

\[ \Delta E = \frac{1}{2} m (v + u)^2 - \frac{1}{2} mv^2 \]

Catch-up collision:

\[ \Delta E_2 = \frac{1}{2} m (v-u)^2 - \frac{1}{2} mv^2 \]

\[ \Delta E = \Delta E_1 + \Delta E_2 \]

\[ \left| \frac{\Delta E}{E} \right| = 2 \frac{u^2}{v^2} \]

\(\rightarrow\) Net energy gain:

\(2^{nd}\) Order Fermi
2\textsuperscript{nd} ORDER FERMI ACCELERATION

There is net energy gain per collision:

\[ \langle \frac{\Delta E}{E} \rangle \propto \frac{u^2}{v^2} \]

\( u \ll v \approx c \): the energy gain per collision is very small

- Statistical reflection on many different clouds in a galaxy
- Stochastic acceleration in magnetized turbulent medium
Energy increases exponentially with # of reflections ($\Delta E \propto E$):

$$\frac{dE}{dt} = \langle \Delta E \rangle v = 4v \left( \frac{V}{v} \right)^2 E \equiv \alpha E$$

$\alpha = \text{Acceleration rate}$

BUT - second order energy gain:

too slow to obtain high energy particles in the few million years that a cosmic ray stays in the galaxy
2\textsuperscript{nd} ORDER FERMI ACCELERATION

✓ Particles accelerated in this statistical process satisfy diffusion-loss equation:

\[
\frac{dN}{dt} \approx -\frac{\partial}{\partial E} [N(E, t)\alpha E] - \frac{N(E, t)}{\tau}
\]

\[\alpha = \text{Acceleration rate} \quad \alpha \equiv 4\nu(V/\nu)^2\]

\[\tau = \text{time a cosmic ray stays in the galaxy}\]

➢ Power Law spectrum:

\[N(E) \approx N_0 E^{-(1+1/\alpha\tau)}\]
2nd ORDER FERMI ACCELERATION

Nice, BUT:

\[ \alpha \sim \frac{\langle V^2 \rangle}{L \nu} \Rightarrow \frac{\langle V^2 \rangle}{Lc} \]

- \( L = 100 \text{pc} \) = mean separation between clouds (scatterers)
- \( \langle V \rangle = 10 \text{ km/s} \) = clouds average velocity
- \( \tau = 2 \times 10^7 \text{anos} \) = decay time of CRs in the Galaxy

\[
\frac{1}{\alpha \tau} = \frac{3 \times 10^{20} \text{cm} \times 3 \times 10^{10} \text{cm/s}}{10^{12} \text{cm}^2/\text{s} \times 6 \times 10^{14} \text{s}} \approx 1.5 \times 10^4
\]

Observed \( \gamma \sim 2.7 \) !!

2nd ORDER FERMI: too slow
1st ORDER FERMI ACCELERATION

REMEMBER:

Head-on collision:

→ Net energy gain:

\[ \Delta E \propto E, \quad \frac{\Delta E}{E} = 2 \frac{uv}{c^2} + \frac{u^2}{c^2} \quad v \approx c \]

\[ \approx \frac{2u}{c} + \frac{u^2}{c^2} \]

1st order(±) 2nd order

Thus we need scattering in a CONVERGING FLOW:

→ acceleration in a SHOCK (Bell et al. 78)
• Particles with higher velocity than the plasma flow may travel against the stream and cross the shock.

• Scatter and interact with magnetic field fluctuations (Alfven waves).

• Shock contains **converging** scatterers because particles experience **higher** (head-on) collision velocities **upstream** than (catch-up) velocities **downstream**.
DIFFUSIVE SHOCK ACCELERATION

picture in the rest frame of the shock front

- reflection in upstream $\Rightarrow$ energy gain $\propto v_{up}/c$
- reflection in downstream $\Rightarrow$ smaller energy loss $\propto v_{down}/c$
- repetition until particle is not scattered back upstream
Every round trip: particle executes one catch-up and one head-on

\[ \frac{\langle \Delta E \rangle}{E} \approx \frac{2(u_1 - u_2)}{v} = \frac{2\Delta u}{v} \]

1st order in \( \sim u/c \)

\[ \rightarrow \text{Fermi I more efficient than Fermi II} \]
DIFFUSIVE SHOCK ACCELERATION

- $\Delta E/E \sim u/c$
- loss of particles downstream in each cycle: $\Delta N_{\text{loss}}/N \propto u/c$

⇒

- energy increases exponentially with # of cycles
- # of participating particles $N$ decreases exponentially with # of cycles

power law for $E > E_{\text{inj}}$

$$f(E) \propto \left( \frac{E}{E_{\text{inj}}} \right)^{-\gamma(M)} \theta(E - E_{\text{inj}})$$
DIFFUSIVE SHOCK ACCELERATION

Power law for $E > E_{\text{inj}}$

\[
f(E) \propto \left( \frac{E}{E_{\text{inj}}} \right)^{-\gamma(M)} \theta(E - E_{\text{inj}})
\]

Mach number $M = v_{\text{upstream}}/c_{\text{sound}}$

Spectral index depends on Mach number
Calculating the spectrum

\[ \beta = \text{average particle energy change/collision:} \]

\[ \mathcal{P} = \text{probability that particle remains in the acceleration regime after one collision} \]

After \( k \) collisions, the number of particles still scattering \( N \):

\[ N = N_0 \mathcal{P}^k \]

\[ E = E_0 \beta^k \]

Thus, eliminating \( k \):

\[ \frac{N}{N_0} = \left( \frac{E}{E_0} \right)^{\ln \mathcal{P}/\ln \beta} \]

\[ dN = KE^{\ln \mathcal{P}/\ln \beta - 1} dE \]
**DIFFUSIVE SHOCK ACCELERATION**

- **Probability**: $P = \text{probability that particle remains in the acceleration region after one collision:}
- \text{number of particles (w/ } \sim c\text{) crossing unit surface area/time: } \frac{1}{4}Nc$
- \text{steady state, the number of particles that cross back upstream: } \frac{1}{4}Nc - u_2N$

$$P = \frac{\frac{1}{4}Nc - u_2N}{\frac{1}{4}Nc} = 1 - \frac{4u_2}{c}$$

Thus: $\ln P = \ln \left(1 - \frac{4u_2}{c}\right) \approx -\frac{4u_2}{c}$ and $\ln \beta = \ln \left(1 + \frac{2\Delta u}{c}\right) \approx \frac{2\Delta u}{c}$

- **For strong shock** $\Rightarrow M >> 1 \Rightarrow \frac{u_1}{u_2} = 4$

$$\frac{\ln P}{\ln \beta} = \frac{-4u_2}{2(u_1 - u_2)} = -\frac{2}{3}$$

$$dN(E) = KE^{-5/3} \, dE$$
LIMITS TO ACCELERATION

- energy gains have to exceed the **losses**:
  - **radiative**: synchrotron radiation, bremsstrahlung, inverse Compton scattering
  - **non-radiative**: coulomb scattering, ionization
  - **catastrophic**: hadronic interactions: $p + p \ldots$
  - **GZK-cut-off**: interaction with CMB photons
ACCELERATION SITES

- **Varying large scale MFs:**
  - pulsars
  - sunspots

- **Diffusive shock acceleration (1st order Fermi):**
  - structure formation shocks (e.g. in merging galaxy clusters)
  - supernovae remnants
  - shocks in jets and active galactic nuclei (AGNs)
  - compact sources (near black holes or neutron stars)
  - galactic winds
  - solar flares?

- **2nd Order Fermi acceleration:**
  - near shock fronts (smaller contribution $\frac{u^2}{c^2} \ll \frac{u}{c}$)
  - turbulent regions in ISM and IGM (scattering @ B irregularities)

- **Acceleration in Reconnection zones (1st order Fermi ?):**
  - solar/stellar flares
  - accretion disks (around black holes, neutron stars,...)
Supernova Remnants (SNRs):

- SN II eject shell – shock front
  \[ M = 10 \, M_{\text{sol}} \]
  \[ v=100 \, \text{km/s} \]
  \[ \text{SN rate} = 10^{-2} \, \text{yr}^{-1} \]

  ➤ Power output:
  \[ P_{\text{SN}} = 5 \times 10^{42} \, \text{J yr}^{-1} \]

- Power to accelerate CRs in the Galaxy:
  - galactic radius: \( R \sim 15 \, \text{kpc} \)
  - thickness: \( D \sim 0.2 \, \text{kpc} \)
  - CRs energy density: \( \rho_E = 1 \, \text{eV cm}^{-3} \)

  \[ P_{\text{CR}} = 2 \times 10^{41} \, \text{J yr}^{-1} \]
Merging clusters of galaxies:

Galaxy cluster Abell 3376

- Mpc-scale supersonic radio-emitting shockwaves
- radio sources (synchrotron radiation..) may be acceleration sites boosting particles up to $10^{19} \text{ eV}$
- hints to subcluster merger activities

Bagchi et al. 2006
Astrophysical Jets:

Shock Acceleration: in internal shocks and terminal shocks (hot spots)

Cygnus A

Acceleration in Magnetic Reconnection
ISM and Star formation regions in galaxies:

galaxy M51

• Synchrotron radiation traces MFs and relativistic electrons – CR sites

• turbulent MFs in spiral arms where ISM, star formation regions, and SNRs

→ diffusive shock acceleration (1st order) behind shocks in stellar jets and SNRs

→ 2nd order Fermi in turbulent ISM
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