Cosmic ray acceleration mechanisms
Project presentation

Discussion group 4

CERN Latinamerican School on High Energy Physics
March 15th-28th, 2009, Medellín

Outline

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Introduction and motivation

- Discovery: Hess, 1912, balloon flights measuring the intensity of ionising radiation as a function of altitude.

- Large energy span: $1 - 10^{20}$ eV

- Made up of protons, nuclei, electrons and other charged particles.

- Expected to be isotropic due to deflection by **B**: don't point back to sources.

- Highest-energy CRs measured to be anisotropic by Pierre Auger Observatory in November 2007.

- How are the highest energies reached?
    - Top-down scenario: CRs are decay products of massive particle.
    - Bottom-up scenario: charged particles are accelerated to high energies in special astrophysical environments
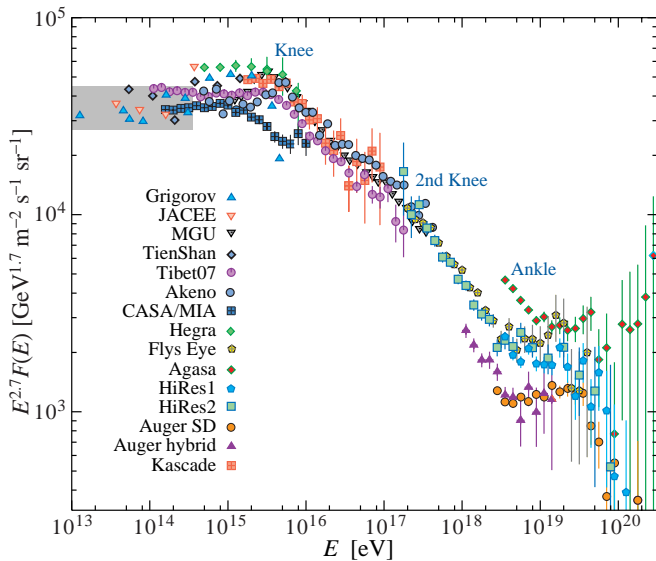
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**Source:** C. Amsler et al., Phys. Lett. **B** 667, 1 (2008)

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Constraints

- Geometry: accelerated particle should be kept inside the source while been acelerated

- Power: the source must possess the required amount of energy to give to the particles

- Radiation losses: the energy lost by a particle as radiation in the accelerating field should not exceed the energy gain

- Interaction losses: the energy lost by interactions with other particles must be less than the energy gain

- Emissivity: the total number and power of sources must explain the observed UHECR flux

Two general forms of acceleration

- One-shot acceleration
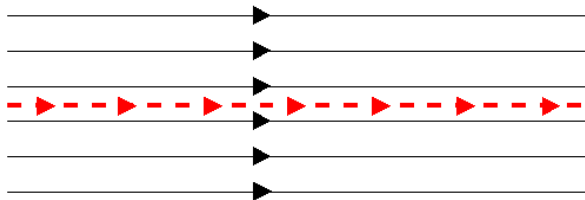
- Diffusive acceleration

Possible sources

Galactic

- SNe II
- Pulsars
- Shock acceleration in SN remnants

Extragalactic

- Active galaxies
- Gamma ray bursts

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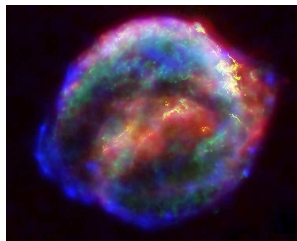- Active galaxies
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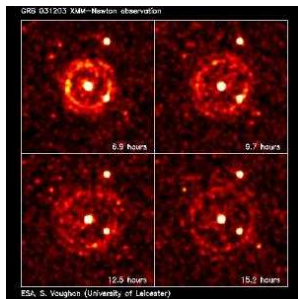Active Galactic Nucleus
(Artist Impression)

Possible sources

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Hillas criterion

- General geometrical criterion to select potential acceleration sites.

- The particle, with Larmor radius R_L, must not leave the site, of linear size R_S, until it reaches the desired energy, i.e.

$$R_L = \Gamma \frac{m v_\perp}{qB} = \Gamma \frac{\varepsilon}{qB} \leq R_S \Rightarrow \varepsilon_{\max} = \varepsilon_H \equiv \Gamma qB R_S$$

- For instance, for a supernova remnant,

$$\begin{cases} R_S \sim 5 \text{ pc} \\ B \sim 10\mu\text{G} \end{cases} \Rightarrow \varepsilon_H \sim 10^{16} \text{ eV}$$
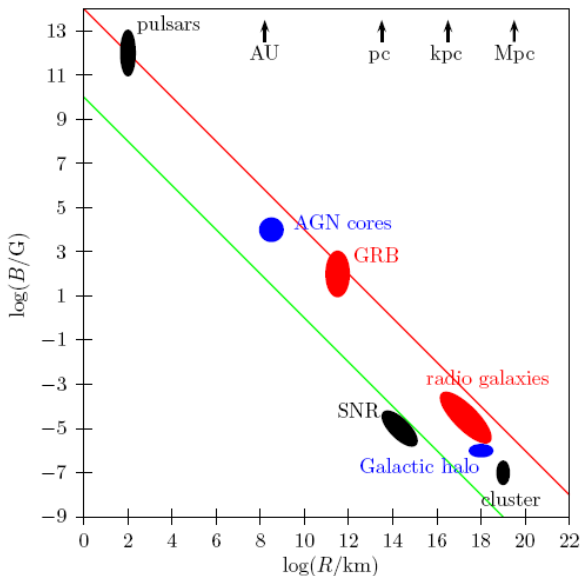
Source: M. Kachelriess, arXiv: astro-ph/0801.4376 (2008)

Energy losses

- For a more realistic description, we can introduce energy losses.

- The maximum energy ε_{loss} a particle can get in an accelerator of infinite size is determined by

$$\frac{d\varepsilon^{(+)}}{dt} = -\frac{d\varepsilon^{(-)}}{dt} \ .$$

- Depending on the conditions at the accelerator, the maximum energy of a particle is limited either by geometrical (Hillas) or energy-loss constraints:

$$\varepsilon_{max} = \min\left(\varepsilon_H, \varepsilon_{loss}\right) \ .$$

- **Diffusive acceleration:** losses dominate by synchrotron radiation; works in shock waves

$$\varepsilon_d \simeq \frac{3}{2} \frac{m^4}{q^4} B^{-2} R^{-1}$$

- **One-shot acceleration with synchrotron-dominated losses:** requires ordered fields throughout the acceleration site; possibly in AGN (for UHECRs)

$$\varepsilon_s = \sqrt{\frac{3}{2}} \frac{m^2}{q^{3/2}} B^{-1/2}$$

- **One-shot acceleration with curvature-dominated losses:** requires ordered fields of very specific configurations (maybe near neutron stars and black holes)

$$\varepsilon_c = \left(\frac{3}{2}\right)^{1/4} \frac{m}{q^{1/4}} B^{1/4} R^{1/2}$$

Summarising...

$$\varepsilon_{\max}(B, R) = \left\{ \begin{array}{ll} \varepsilon_H(B, R), & B \le B_0(R) \\ \varepsilon_{\text{loss}}(B, R), & B > B_0(R) \end{array} \right. ,$$

with

$$B_0(R) = 3.16 \times 10^{-3} \text{ G } \frac{A^{4/3}}{Z^{5/3}} \left(\frac{R}{\text{kpc}} \right)^{-2/3}$$

$$\varepsilon_{\text{loss}}(B, R) = \left\{ \begin{array}{ll} \varepsilon_d(B, R), & \text{for diffuse acceleration} \\ \varepsilon_s(B, R), & \text{for inductive acceleration with synchrotron-dominated losses} \\ \varepsilon_c(B, R), & \text{for inductive acceleration with curvature-dominated losses} \end{array} \right.$$

- Thick line: lower boundary due to Hillas criterion
- Light grey: allowed by one-shot acceleration with curvature-dominated losses
- Grey: allowed by one-shot acceleration with synchrotron-dominated losses
- Dark grey: allowed by both one-shot and diffusive acceleration

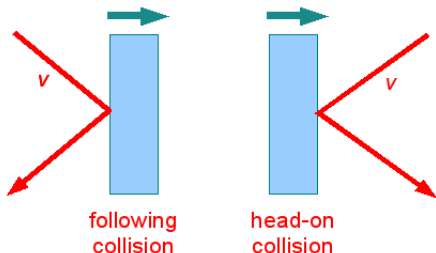**Source:** K. Ptitsyna and S. Troitsky, arXiv: astro-ph/0808.0367 (2008)
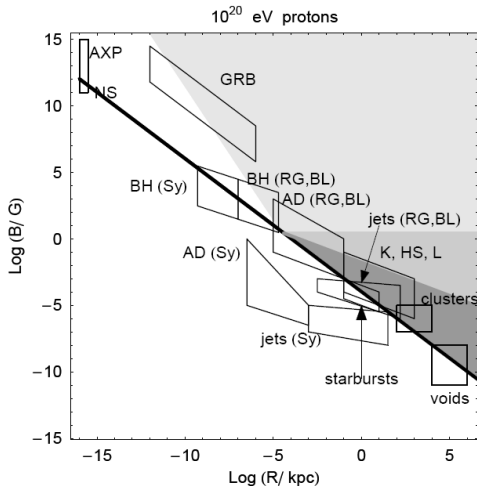
10^{20} eV protons

Outline

Second-order Fermi acceleration

- Proposed by Fermi in 1949.
- Collision of relativistic particles on "magnetic mirrors".
- Energy gain per reflection $\propto (v/c)^2$.

following collision   head-on collision

- Rate of energy increase:

$$\frac{dE}{dt} = \frac{4}{3} \left(\frac{v^2}{cL} \right) E = \alpha E .$$

- The particle remains inside the acceleration region for a time t_{esc}.
- Using a diffusion-loss equation we find, in the steady state,

$$\frac{dN(E)}{dE} = - \left(1 + \frac{1}{\alpha t_{esc}} \right) \frac{N(E)}{E} \Rightarrow N(E) = \text{const.} \times E^{-\left(1 + \frac{1}{\alpha t_{esc}} \right)}$$

Problems with second-order Fermi acceleration:

- Cloud density too low $\Rightarrow \sim 1$ collision per year $\Rightarrow$ slow energy gain

- No reason why exponent should be equal to the observed value of ~ 2.7 isotropically

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First-order Fermi acceleration

- Relativistic particles, supersonic magnetic shocks.

- Energy gain per crossing $\propto v/c$.

- Average energy after one collision: $E = \beta E_o$

downstream → upstream   downstream ← upstream
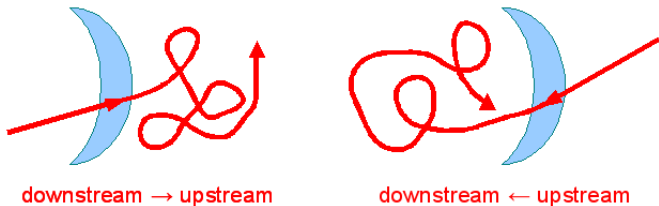
- Same energy gain in downstream → upstream and upstream → downstream crossing.

- Probability that a particle remains inside the acceleration region after one collision: P.

- After k collisions: $N = N_o P^k$ with energies $E = E_o \beta^k$; so

$$N(E)\, dE = \text{ const.} \times E^{-1 + \ln(P)/\ln(\beta)} dE$$

- Possible to show that $\ln(P)/\ln(\beta) = -1$ using kinematics, so that

$$N(E)\, dE = \text{ const.} \times E^{-2} dE$$

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Summary

- ● CRs have a rich spectrum:
    - ▸ Knee: 10^{15}-10^{16} eV
    - ▸ Ankle: $\sim 4 \times 10^{19}$ eV

- ● Mechanism to accelerate to highest energies still unknown.

- ● However there *are* general constraints that limit possible sources, notably
    - ▸ Hillas criterion
    - ▸ Energy losses

- ● Acceleration can occur either as ...
    - ▸ one-shot
    - ▸ diffusive

- ● Most favoured diffusive mechanism: (first-order) Fermi acceleration.

- ● Wait for better UHECR correlation results from Auger!

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