

Cosmic ray acceleration mechanisms

Project presentation

Discussion group 4

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

<http://physicschool.web.cern.ch/PhysicSchool/LatAmSchool/2009/Presentations/pDG1.pdf>

Outline

- 1 Introduction
- 2 General constraints on acceleration sites
 - Two general forms of acceleration
 - Possible sources
 - Hillas criterion
 - Energy losses
- 3 Fermi acceleration
 - Second-order Fermi acceleration
 - First-order Fermi acceleration
- 4 Summary

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Introduction and motivation

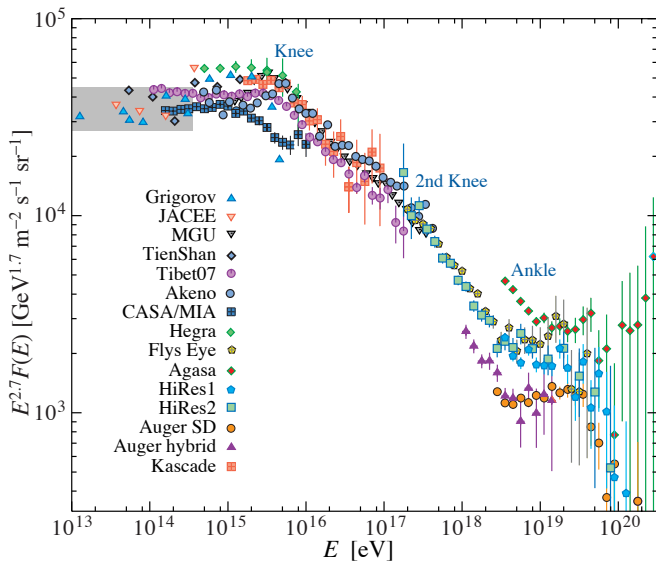
- **Discovery:** Hess, 1912, balloon flights measuring the intensity of ionising radiation as a function of altitude.
- Large energy span: $1 - 10^{20}$ eV
- Made up of protons, nuclei, electrons and other charged particles.
- Expected to be isotropic due to deflection by **B**: don't point back to sources.
- 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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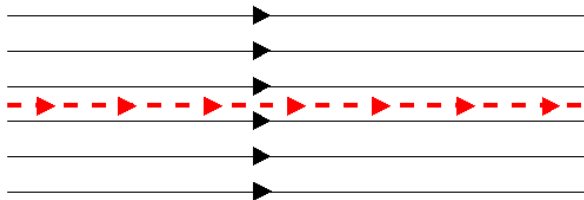
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Constraints

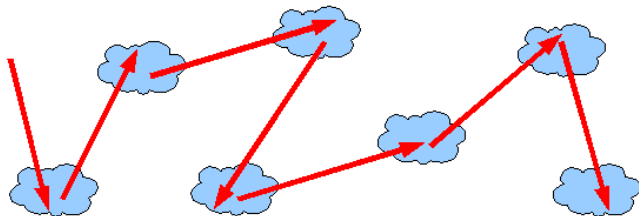
- **Geometry:** accelerated particle should be kept inside the source while been accelerated
- **Power:** the source must possess the required amount of energy to give to the particles
- **Radiation losses:** the energy lost by a particle as radiation in the accelerating field should not exceed the energy 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

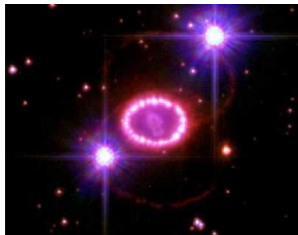
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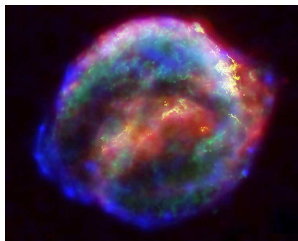
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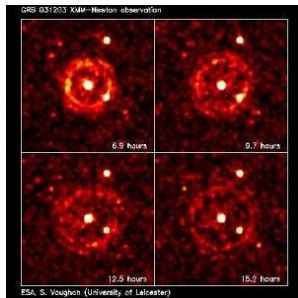
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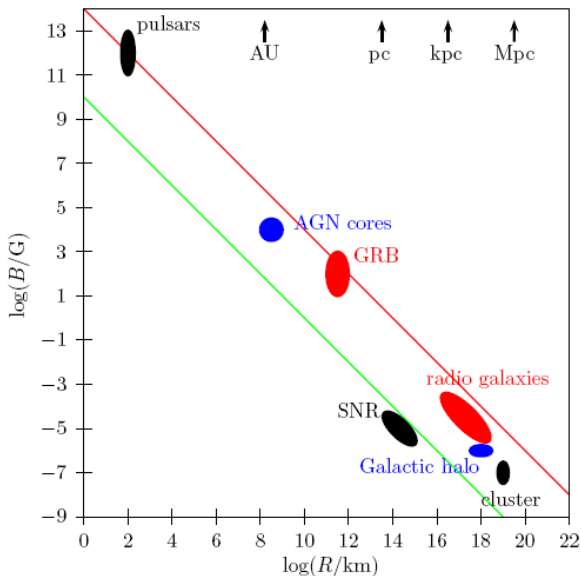
Hillas criterion

- 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.

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

- 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 $\varepsilon_{\text{loss}}$ 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:

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

- **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...

$$\varepsilon_{\max}(B, R) = \begin{cases} \varepsilon_H(B, R), & B \leq B_0(R) \\ \varepsilon_{\text{loss}}(B, R), & B > B_0(R) \end{cases},$$

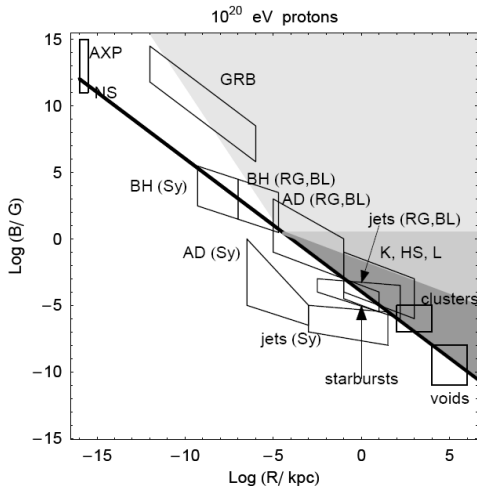
with

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

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

- 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)

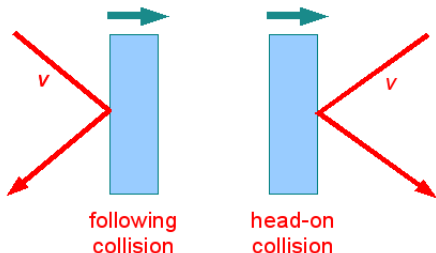


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Second-order Fermi acceleration

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



- 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,

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

Problems with second-order Fermi acceleration:

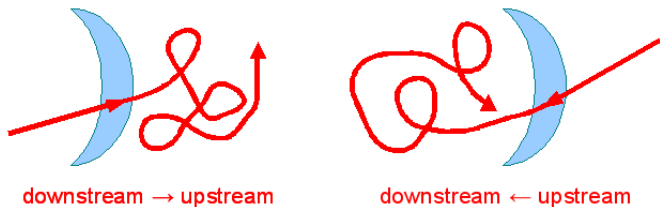
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First-order Fermi acceleration

- Relativistic particles, supersonic magnetic shocks.
- Energy gain per crossing $\propto v/c$.
- Average energy after one collision: $E = \beta E_0$



- Same energy gain in **downstream \rightarrow upstream** and **upstream \rightarrow 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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 - ▶ Ankle: $\sim 4 \times 10^{19}$ eV
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- However there *are* general constraints that limit possible sources, notably
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