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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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

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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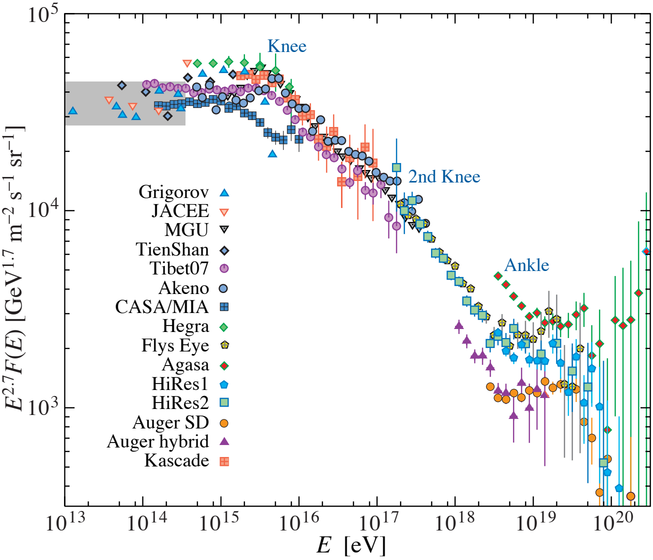

Source: C. Amsler et al., Phys. Lett. **B** 667, 1 (2008)

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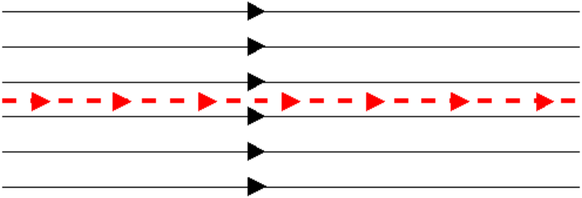
Constraints

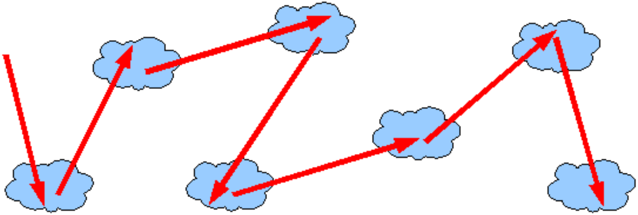
- Geometry: accelerated particle should be kept inside the source while been acelerated
- Power: the source must possess the required amount of energy to give to the particles
- Radiation losses: the energy lost by a particle as radiation in the accelerating field should not exceed the energy gain
-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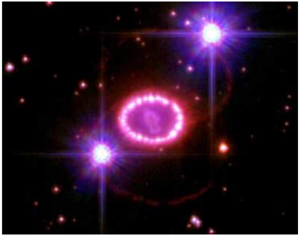

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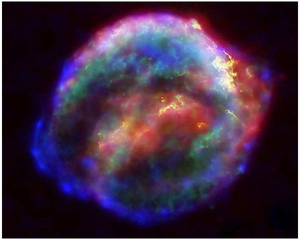

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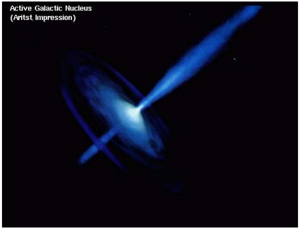

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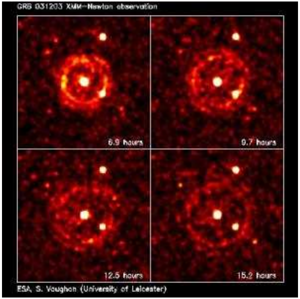


GRB 031203 XMM–Newton observation

ESA, S. Vaughan (University of Leicester)

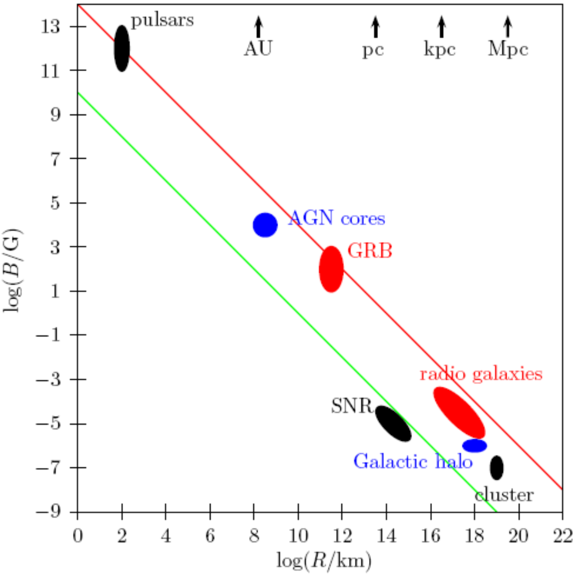
Hillas criterion

- 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.

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

- For instance, for a supernova remnant,

$$\left\{ \begin{array}{l} R_S \sim 5\ \mathrm{pc} \\ B \sim 10\mu\mathrm{G} \end{array} \right. \Rightarrow \varepsilon_H \sim 10^{16}\ \mathrm{eV}$$



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
$$\frac{d\varepsilon^{(+)}}{dt} = -\frac{d\varepsilon^{(-)}}{dt} \quad .$$
- Depending on the conditions at the accelerator, the maximum energy of a particle is limited either by geometrical (Hillas) or energy-loss constraints:
$$\varepsilon_{\text{max}} = \min\left(\varepsilon_H, \varepsilon_{\text{loss}}\right) \quad .$$

- **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...

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

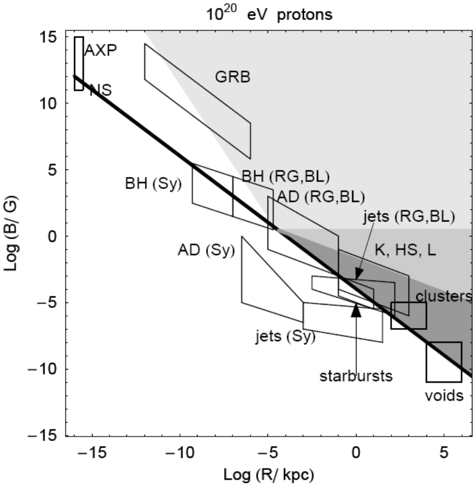
with

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

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

- 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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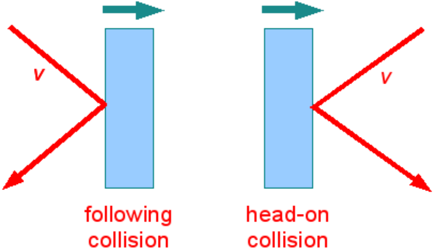
Second-order Fermi acceleration

- 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 $t_{\rm esc}$.
- Using a diffusion-loss equation we find, in the steady state,

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

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 $\sim$ 2.7 isotropically

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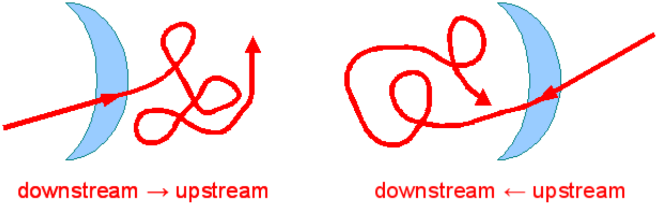
First-order Fermi acceleration

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



- 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
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- Acceleration can occur either as ...
  - one-shot
  - diffusive
- Most favoured diffusive mechanism: (first-order) Fermi acceleration.
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