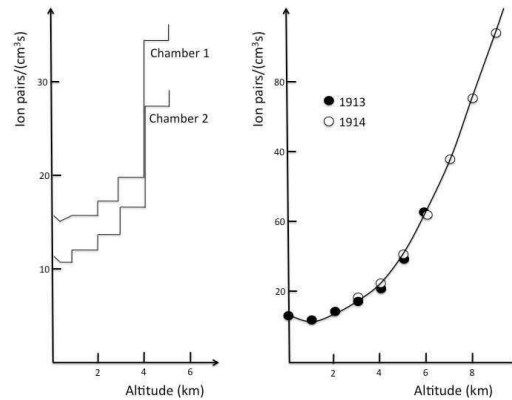
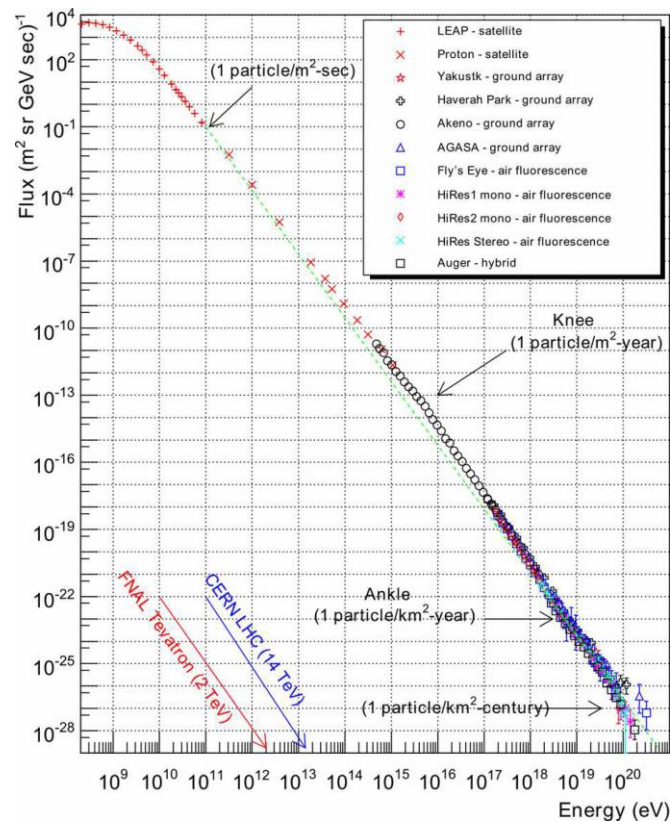


Cosmic rays

1. Primary cosmic rays and cosmic ray acceleration



Balloon measurements performed by Hess (1912, Nobel Prize 1927) and Kolhörster (1913 and 1914) revealed ionizing radiation. Flux increases with increasing height.

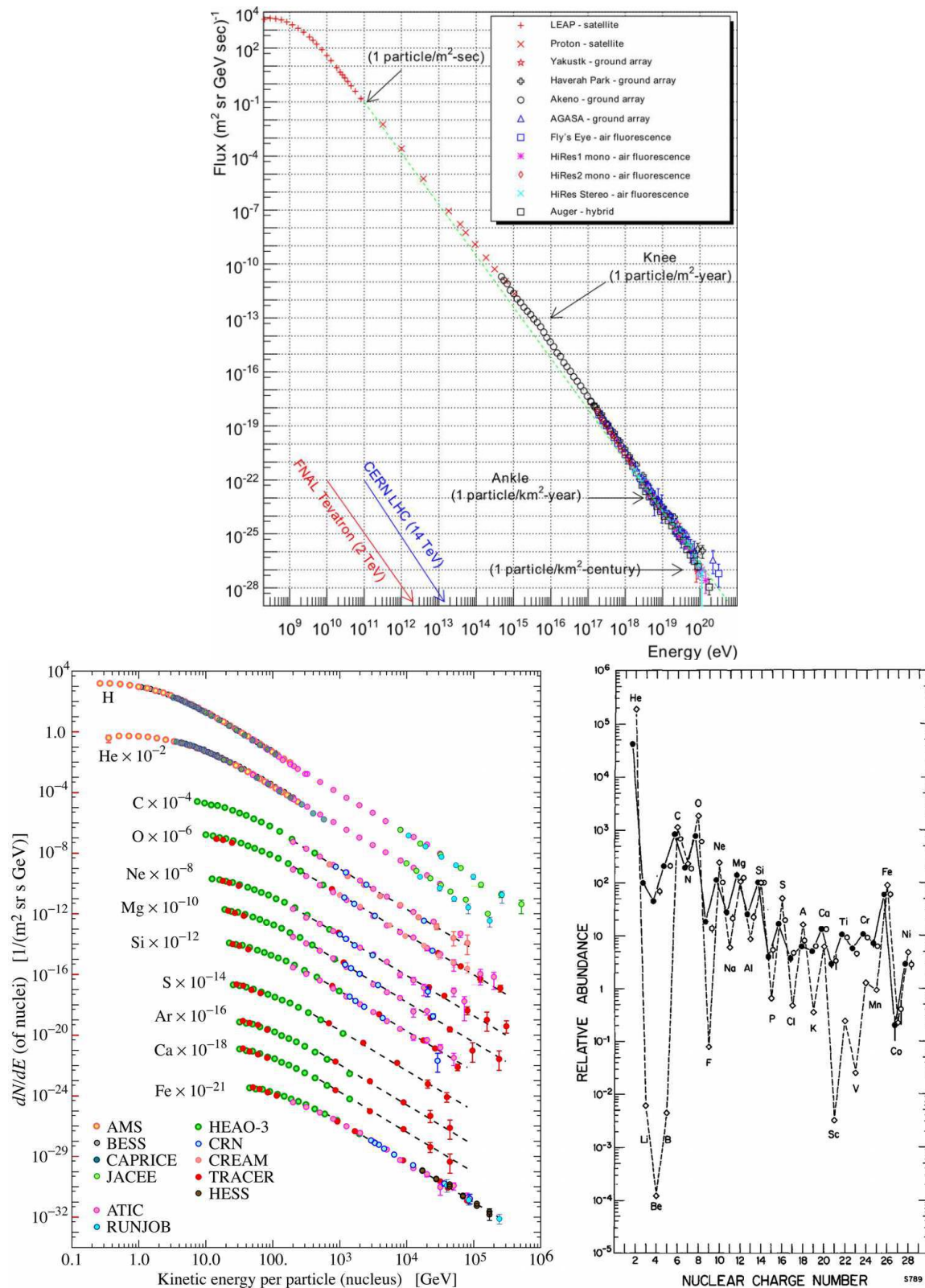


Nowadays we know: primary cosmic ray component (outside earth atmosphere) follows power law

$$\frac{dF}{dE d\Omega} = I_0 \left(\frac{E}{E_0} \right)^\alpha = 1.8 \cdot 10^4 \left(\frac{E}{\text{GeV}} \right)^{-2.7} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}$$

Below 10^{16} eV.

For $3 \cdot 10^{16} \text{ eV} < E < 10^{18} \text{ eV}$: $\alpha \sim 3.0$



The abundance of elements in cosmic rays is similar to the one of solar system material. A few clear differences:

1. Higher abundance of protons and helium nuclei in solar system
2. Li, Be and B as well as Sc, Ti, V, Cr and Mn are significantly less abundant in cosmic rays

Difference in proton and He abundances not understood. Could be source specific or propagation specific (more difficult to accelerate low mass nuclei?)

The lower abundance in Li, Be, B are thought to be due to spallation processes of C and O with H and He of interstellar medium. Higher Sc, Ti, V and Cr abundance due to spallation processes of Fe.

Acceleration mechanism:

Sources must fulfill the following properties:

- acceleration mechanism should naturally produce a power law spectrum
- some (at least) must reach $E \sim 10^{20} \text{ eV}$
- should reproduce the observed chemical abundances

Known possible mechanisms have in common:

- state of matter inside the accelerator is plasma
- acceleration via collision-less deflection in magnetic field

Look for sources with extreme conditions:

- ➔ SN explosions: Creation of shock waves with respect to interstellar medium.
- ➔ Accretion of into black holes
- ➔ Active galactic nuclei (supermassive black holes)
- ➔ ???

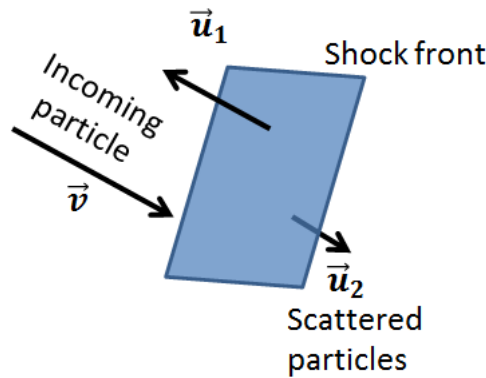
Problem: charged with $E < 10^{18} \text{ eV}$ component being deflected ➔ no directional information.

- ➔ Hadronic component of cosmic rays isotropic!

This is not the case for **Neutrinos & Photons!**

➔ Neutrino telescopes (ICE Cube) & High energy gamma astronomy (H.E.S.S./ MAGIC/CTA...)

Diffusive Shock Acceleration: (also 1st order Fermi acceleration):



Particle reflected from shock front gains energy. Let \vec{u}_1 be the velocity of the shock front, \vec{u}_2 the velocity of particles streaming away from shock front and \vec{v} the velocity of incoming particle \rightarrow energy gain of reflected particle

$$\Delta E = \frac{1}{2}m(v + (u_1 - u_2))^2 - \frac{1}{2}mv^2 = \frac{1}{2}m(2v(u_1 - u_2) + (u_1 - u_2)^2)$$

$$\text{For } v \gg u_{1,2} \text{ \& } u_1 > u_2: \quad \frac{\Delta E}{E} \cong \frac{2(u_1 - u_2)}{v}$$

Relativistic treatment:

energy gain per shock crossing (ultra relativist. Limit $p \approx E/c$):

$$E' = \gamma(E - up_x) \approx \gamma(E + \beta E \cos(\theta))$$

averaging θ :

- probability for direction: $[\theta, \theta + d\theta]: P \propto \sin(\theta)$
- probability for shock crossing per time int.: $P \propto \cos(\theta)$
- $\langle \Delta E/E \rangle = \beta \int_0^{2\pi} 2\cos^2(\theta)\sin(\theta)d\theta = 2/3 \beta$
- after full cycle: $\langle \Delta E/E \rangle = 4/3 \beta \rightarrow$ first order in beta!

If there are two shock fronts with velocities v_1 and v_2 from the same source, particles can be reflected back and forth between the two fronts. Usually inner shock front moves faster than outer one: $v_1 < v_2$

Reflection on outer front leads to energy loss $-\Delta E_o$, while reflection on inner one to energy gain ΔE_i :

$$\Delta E_{o,i} = \frac{1}{2}m(v + v_{1/2})^2 - \frac{1}{2}mv^2 = \frac{1}{2}m(v_{1/2}^2 + 2vv_{1/2})$$

\rightarrow On average energy gain ΔE since usually (1st shock "blasts away interstellar medium, hence has higher impedance than 2nd shock)

$$v_2 > v_1$$

$$\Delta E = \Delta E_i - \Delta E_o = \frac{1}{2}m(v_1^2 + v_2^2 + 2v(v_2 - v_1))$$

$$\text{For } v \gg v_{1/2}: \Delta E \cong mv\Delta v \rightarrow \frac{\Delta E}{E} \cong 2 \frac{\Delta v}{v}$$

Accelerations up to $\sim 100 \text{ TeV} = 10^{14} \text{ eV}$ possible.

Fermi mechanism (also 2nd order Fermi acceleration):

Acceleration in turbulent plasma:

Interaction with “magnetic mirrors” moving at random velocities with isotropic directions.

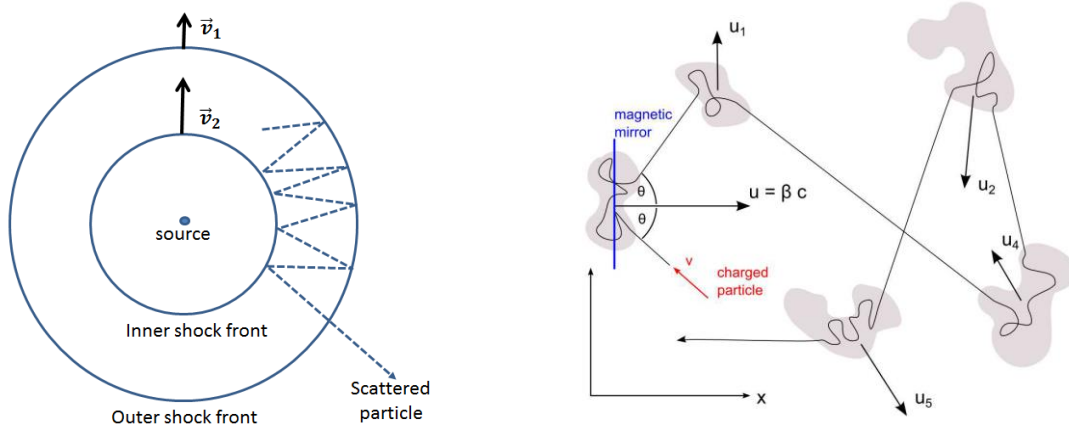
“magnetic mirrors” moving with average velocity $u = |\vec{u}|$, particle has velocity \vec{v} .

For $\vec{u} \uparrow \uparrow \vec{v} \rightarrow$ Particle loses energy: $\Delta E_{\uparrow\uparrow} = \frac{1}{2}m(v-u)^2 - \frac{1}{2}mv^2 = \frac{1}{2}m(-2uv + u^2)$

For $\vec{u} \uparrow \downarrow \vec{v} \rightarrow$ Particle gains energy: $\Delta E_{\uparrow\downarrow} = \frac{1}{2}m(v+u)^2 - \frac{1}{2}mv^2 = \frac{1}{2}m(2uv + u^2)$

On average energy gain: $\Delta E = \Delta E_{\uparrow\uparrow} + \Delta E_{\uparrow\downarrow} = mu^2 \rightarrow \frac{\Delta E}{E} \cong 2 \left(\frac{u}{v}\right)^2$

Since $u \ll v$: Energy gain per reflection very low \rightarrow Needs lots of time



1. and 2. order Fermi acceleration mechanism

Power law distribution:

Let energy gain per reflection be proportional to incident particles energy: $\Delta E = \varepsilon E$

\rightarrow After n reflections particle will have gained energy

$$E_n = E_0(1 + \varepsilon)^n$$

\rightarrow to gain energy E in to the number of reflections needed is given by

$$N = \frac{\ln\left(\frac{E}{E_0}\right)}{\ln(1 + \varepsilon)}$$

With P_e the probability that particle is not reflected (i.e. is lost) the probability that particle actually makes N reflections is given by

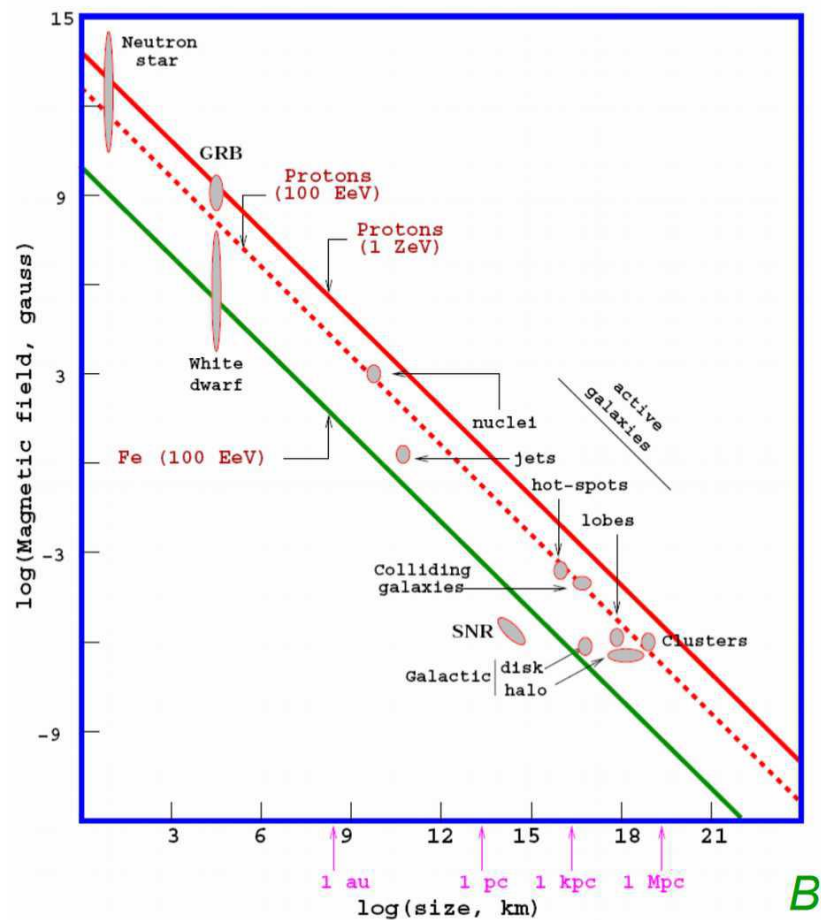
$$(1 - P_e)^N$$

→ Fraction of particles with energy $> E$ is

$$N(> E) \propto \sum_{m=N}^{\infty} (1 - P_e)^m = \frac{(1 - P_e)^N}{P_e}$$

With equ. above:

$$N(> E) \propto \frac{1}{P_e} \left(\frac{E}{E_0} \right)^\gamma \quad \text{with } \gamma = \frac{\ln(\frac{1}{1-P_e})}{\ln(1+\epsilon)}$$



Hillas plot: B- field of source vs.size of source. Given size and B-field of an object the maximum energy to which a charged particles can be accelerated to can be calculated (lines for protons with different energy). Some potential sources for acceleration are plotted.

In general charged cosmic ray particles can be bound by magnetic field if Larmor radius smaller than object:

$$r = \frac{p}{Z e B}$$

where p is the momentum Z the charge number of the particle and B the field strength.

$$\left(\frac{r}{A.U.}\right) = 2 \cdot 10^2 \left(\frac{p}{TeV}\right) \left(\frac{\mu G}{B}\right)$$

Typical values for $B \sim 10 \mu G \rightarrow$ for particle with $p \sim 5 TeV$:

$$r(10 \mu G, 5 TeV) \sim 100 A.U. \rightarrow \text{solar system}$$

Energy for which proton has larger Larmor radius than size of galaxy $R_{gal} \sim 100 kpc$:

$E \gtrsim 10^{19} eV \rightarrow$ Cosmic rays with $E \gtrsim 10^{19} eV$ must have extra galactic origin (ankle in spectrum)!

There are transitions in the cosmic ray energy spectral index (knee and ankle) that are believed to be due to upper bounds of different acceleration mechanisms.

GZK cutoff for protons:

Greisen, Zatsepin, Kuzmin predicted cut-off due to reaction of UHE cosmic ray protons off CMB (1966) due to reactions

$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow p + \pi^0$$

$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

at $E \sim 10^{20} eV$ (Can be easily calculated using four momenta)

Above this energy: mean free path of protons $\sim 8 \text{ Mpc} \rightarrow$ half distance to nearest large cluster of galaxies (Virgo cluster)

\rightarrow Power law of spectrum should be suppressed above $\sim 10^{20} eV$

For heavier nuclei: cutoff scales with A: mass number!