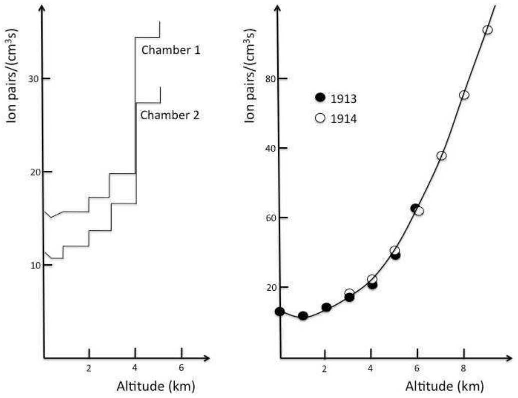
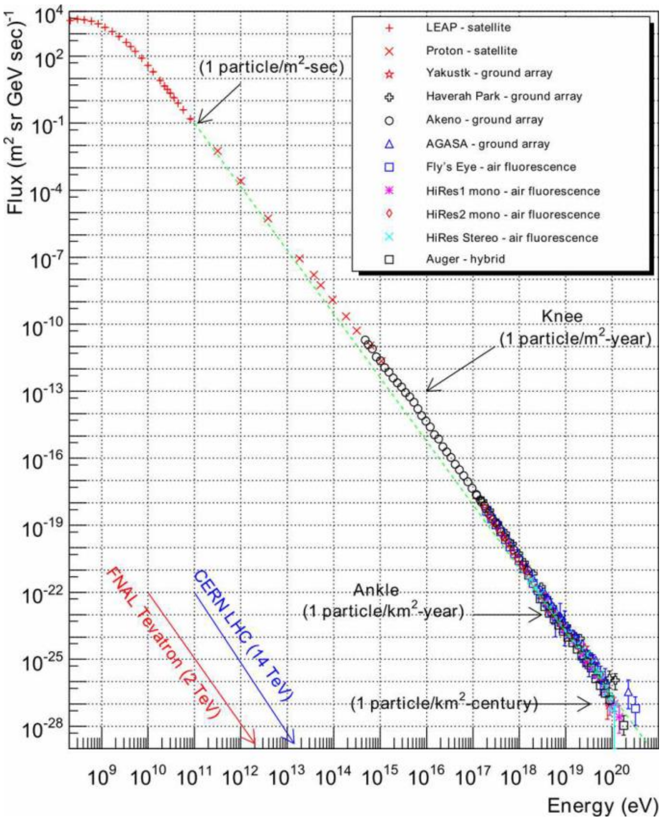
Cosmic rays

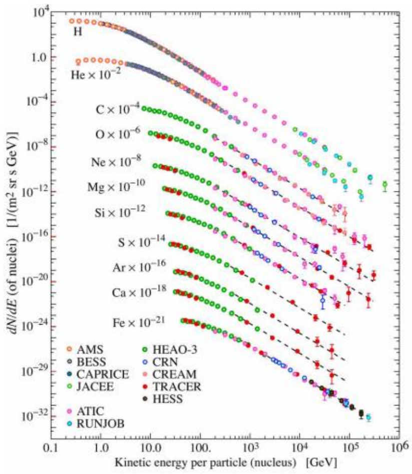
1. Primary cosmic rays and cosmic ray acceleration

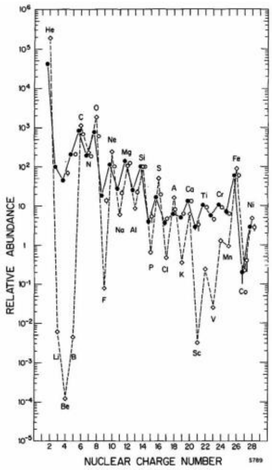


Balloon measurements in 1913 and 1914 performed by Hess (1912) and Kolhörster (1913 and 1914) revealed ionizing radiation.



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





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 more 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.

GZK cutoff:

- Greisen, Zatsepin, Kuzmin predicted cut-off at $E \sim 10^{19} eV$(1966)
- $p + \gamma_{CMB} \to \Delta^+$ and$p + \gamma_{CMB} \to \Delta^+ \to n + \pi^+$possible in the proton-photon center of mass frame
- A few years ago the AGASA experiment showed controversial results without GZK cut-off → Now: good agreement!

<u>Acceleration mechanism:</u>

Sources must fulfill the following properties:

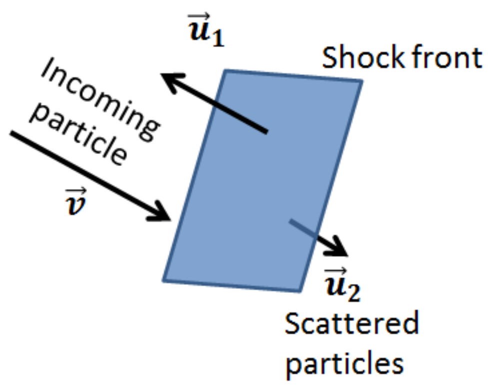
- acceleration mechanism should naturally produce a power law spectrum
- some (at least) must reach $E \sim 10^{20} eV$
- should reproduce the observed chemical abundances

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.

<u>Diffusive Shock Acceleration: (also 1st order Fermi acceleration):</u>



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 → energy gain of reflected particle

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

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

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:

- probablility 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: $\langle \Delta E/E \rangle = 4/3\,\beta$→ 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 for the between the two fronts. Ususally 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_o:

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

→On average energy gain ΔE since $v_2 > v_1$

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

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 $\sim 100\ TeV = 10^{14} eV$ possible.

<u>Fermi mechanism (also 2nd order Fermi acceleration):</u>

Acceleration in turbulent plasma:

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

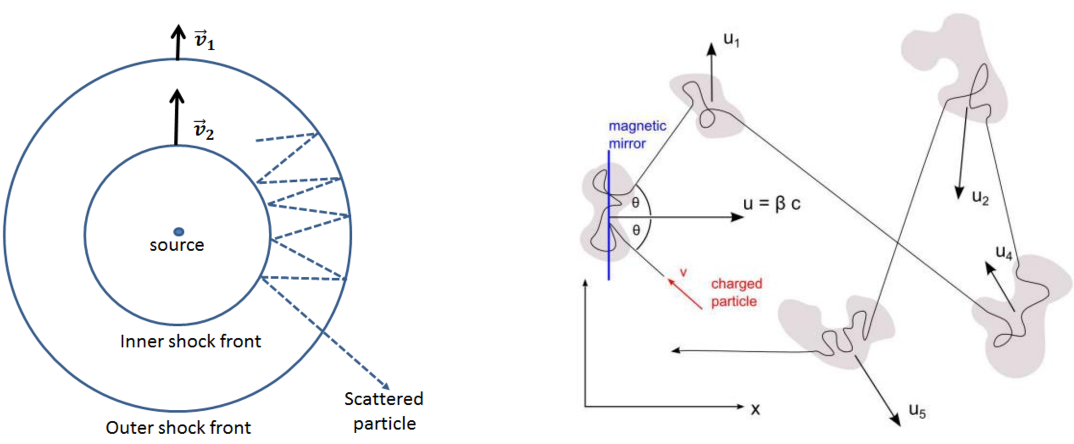
“magnetic mirrors” moving with average velocity $u = |\vec{u}|$, particle has velocity $\vec{v}$.

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

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

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

Since $u \ll v$: Energy gain per reflection very low → 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: $\Delta E = \varepsilon E$
→ After n reflections particle will have gained energy

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

→ to gain enery 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

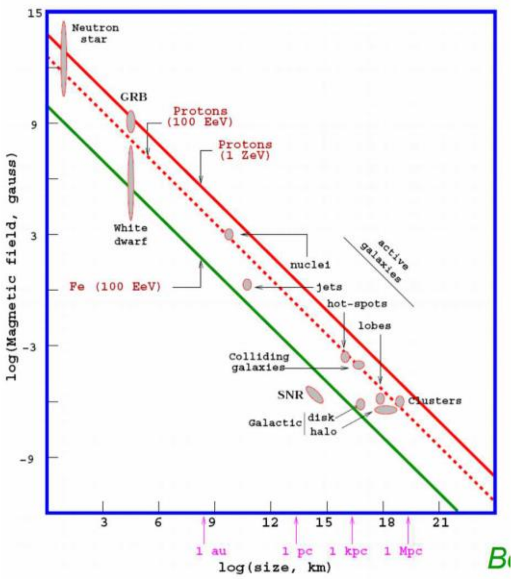
$$(1-P_e)^N$$

→ 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. (N=):

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



Hillas plot

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 valus for $B \sim 10\mu G$ → for particle with $p \sim 5\ TeV$:

$$r(10\mu G, 5\ TeV) \sim 100\ A.U.$$

Energy for which proton has larger Larmor radius than size of galaxy $R_{gal} \sim 100\ kpc$:
$E \gtrsim\ 10^{19}\ eV$ → Cosmic rays with $E \gtrsim\ 10^{19}\ eV$ must have extra galactic origin(ankle in spectrum)!

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