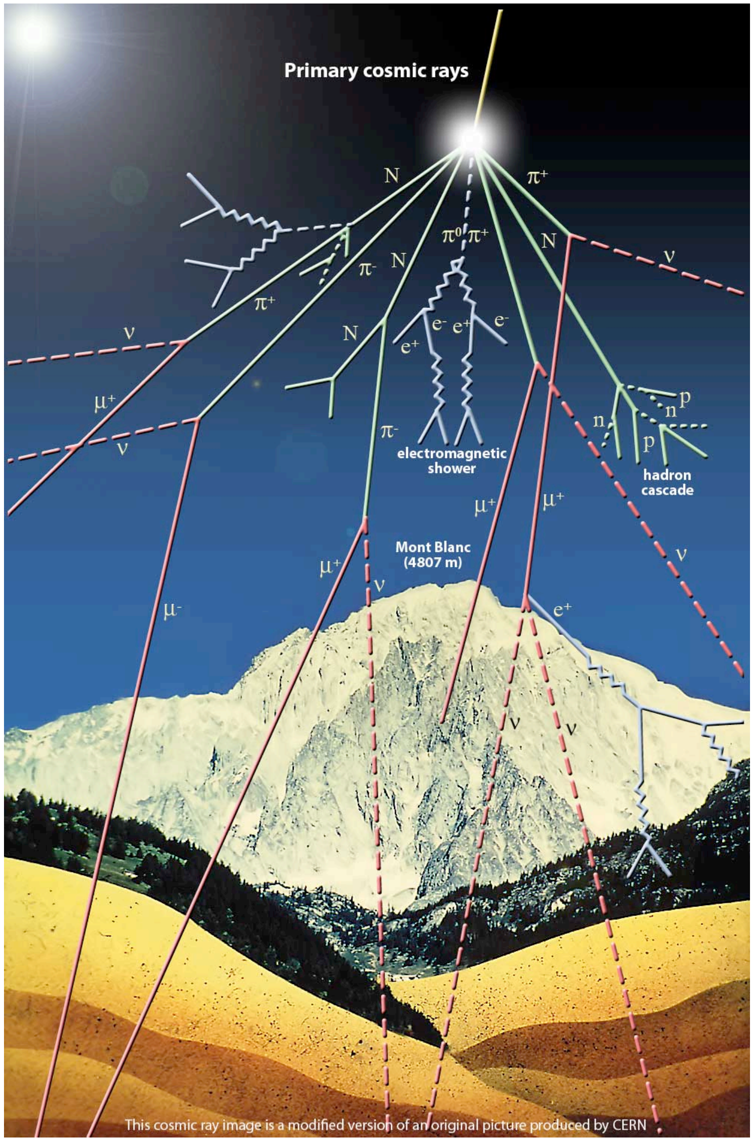
Cosmic Rays



- Historical hints
- Primary Cosmic Rays:
  - Cosmic Ray Energy Spectrum
  - Composition
  - Origin and Propagation
  - The knee region and the ankle
- Secondary CRs:
  - shower development
  - interactions
- Detection:
  - primary CRs: BESS, PAMELA
  - secondary CRs: EAS (Pierre Auger and Hires)

Historical hints

1900: electroscopes discharged even far from natural radioactivity sources
Charged using a rod and the ionization was measured from the rate at which the leaves got together due to leakage currents associated with ionization

Hess 1912 (1936 Nobel prize) and Kolhörster 1914 manned balloon ascents up to 5-9 km: the average ionization increases with altitude
'A radiation of very high penetrating power enters our atmosphere from above'
Cosmic Rays were named by Millikan (1925) that measured ionization underwater (he observed the more penetrating muon component not the elctromagnetic as in the atmosphere)
After 1929 it was realized they are made of charged particles reaching the Earth in groups - atmospheric showers

Questions

- Which are their sources and where are they located?
- How do cosmic rays propagate from the sources to the Earth and how their chemical composition is changed?

  Do they fill:

  1) the solar system
  2) the disc of the Galaxy 0.3 kpc **1pc = 3 ly = 3.1 10^{13} km**
  3) the halo of the Galaxy 10 kpc
  4) the local group 2 Mpc
  5) the local supercluster (Virgo) 20 Mpc
  6) whole Universe c/H_0

The observables to be used for answering this questions are the spectrum, the chemical composition, their direction.

High altitude balloons, rockets and satellites are used to study the CRs in the solar system. In the composition of this 'primary' CRs at the boundary of the Earth's atmosphere (>40 km) there is a component of solar origin but the main component above 1 GeV reaches us from the interstellar space. There are good reasons to believe that CRs are formed in the Galaxy except for those with E > 10^{17} eV (but their contribution to the energy density and flux is negligible)

Primary Cosmic Rays

Flux of stable (>10^6 yrs) charged particles and nuclei

Primary Cosmic Rays: accelerated at astrophysical sources

- Protons ~87%
- He ~12%
- 1% heavier nuclei: C, O, Fe and other ionized nuclei synthesized in stars
- 2% electrons
- γ-rays, neutrinos
- There may be primary components of anti-p and e^+ (antimatter in the Universe?)

But composition varies with energy (bulk of CR is at 1 GeV).

Secondaries: particles produced in interactions of primaries with interstellar gas

Also particles produced in atmospheric showers

(Li, Be, B, anti-p, e^+)

Aside from particles produced in solar flares, they come from outside the solar system

Composition of CRs in the solar system and in the Galaxy

All stable elements of periodic table are found in CRs and abundances are very similar to solar system one.

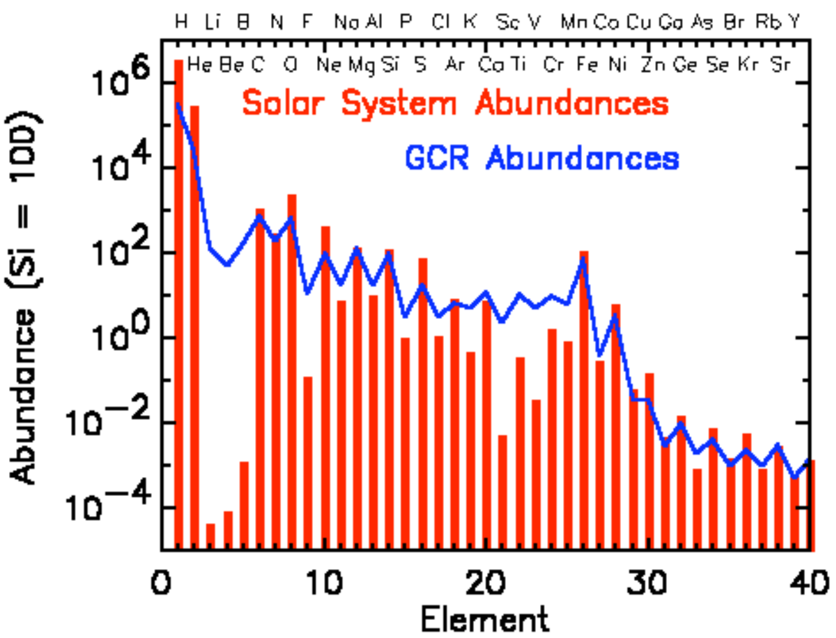
Taking Silicon abundance as reference (by definition its abundance is assumed equal for both - it is easy to measure) the relative abundances of the elements in the solar system and in galactic CRs are compared:

- Less H and He in CRs than in solar system
- More light elements (Li, Be, B) in CRs than solar system
- The abundances of odd Z elements are larger (odd-even effect)
- More sub-Fe elements in CRs

Li, B, Be are not produced in star nucleosynthesis but are the result of spallation on interstellar matter

= collisions between IM and CRs. These are fragmented resulting in nuclei with charge and mass numbers just less than those of the common elements

H and He: since Z = 1 difficult to ionize and accelerate them?



Composition of CRs

- The odd/even effect is due to the fact that nuclei with odd Z and/or A are weaker bound and more frequent products in thermonuclear reactions. Extremely stable nuclei occur for filled shells ('magic nuclei') corresponding to magic numbers (2,8,20,50,82,126) that refer separately to n and p. Double magic nuclei like He and O are particularly stable and hence abundant.
- Increased abundances of Li, Be, B in CRs due to spallation of heavier elements (such as C and O). Sub-Fe come from fragmentation of Fe that is relatively abundant.
- Spallation interactions and resulting abundances give interstellar thickness and average CR lifetime

Horandel astro-ph/0501251

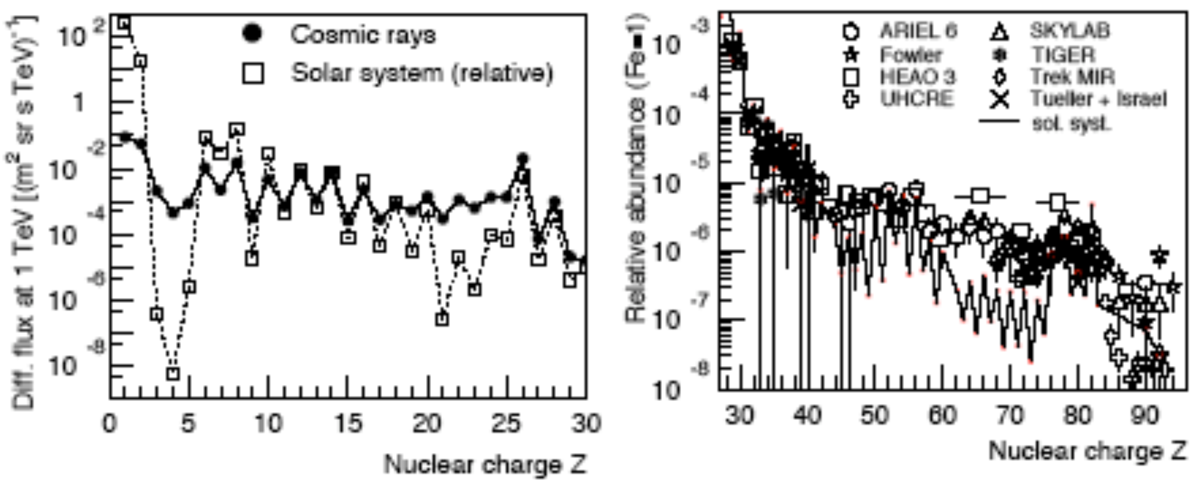


Fig. 4. *Left*: Abundance of elements ($Z \le 28$) in CRs[43,36] at 1 TeV. *Right*: Relative abundance of CR elements ($Z > 28$) normalized to Fe≡ 1 from various experiments around 1 GeV/n. For references see[36,6]. For comparison, abundances in the solar system[42] are presented as well, normalized to Si (*left*) and to Fe (*right*).

Rigidity

Rigidity in volts = energy/electric charge = gyroradius*magnetic field
Measures the deflection of a particle of charge Z and momentum p in B
Lorentz force: $\mathbf{F} = Ze\,\mathbf{v} \times \mathbf{B}$
If the particle moves in a plane perpendicular to B $\Rightarrow$circular motion:
$ZevB = mv^2/r_L$
For a relativistic particle

$$\frac{d}{dt}(\gamma m\mathbf{v}) = Ze(\mathbf{v}\times\mathbf{B})$$

$$\frac{d}{dt}(\gamma m\mathbf{v}) = m\gamma\frac{d\mathbf{v}}{dt} - \frac{1}{2}\left(1-\frac{\mathbf{v}\cdot\mathbf{v}}{c^2}\right)^{-3/2}\left(-2\frac{\mathbf{a}\cdot\mathbf{v}}{c^2}\right) =$$

$$= m\gamma\frac{d\mathbf{v}}{dt} + m\gamma^3\mathbf{v}\left(\frac{\mathbf{a}\cdot\mathbf{v}}{c^2}\right)$$

=0 in a magnetic field

$$m\gamma\frac{d\mathbf{v}}{dt} = Ze(\mathbf{v}\times\mathbf{B})$$

If $\mathbf{v} \perp \mathbf{B} \Rightarrow ZevB/m\gamma = v^2/r_L$ and $p = m\gamma\,\mathbf{v}$

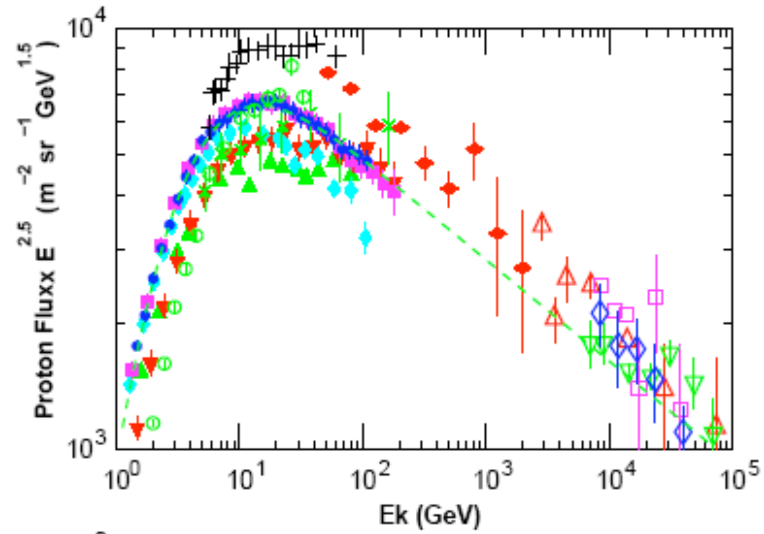
$$R = \frac{pc}{Ze}$$ in Volts

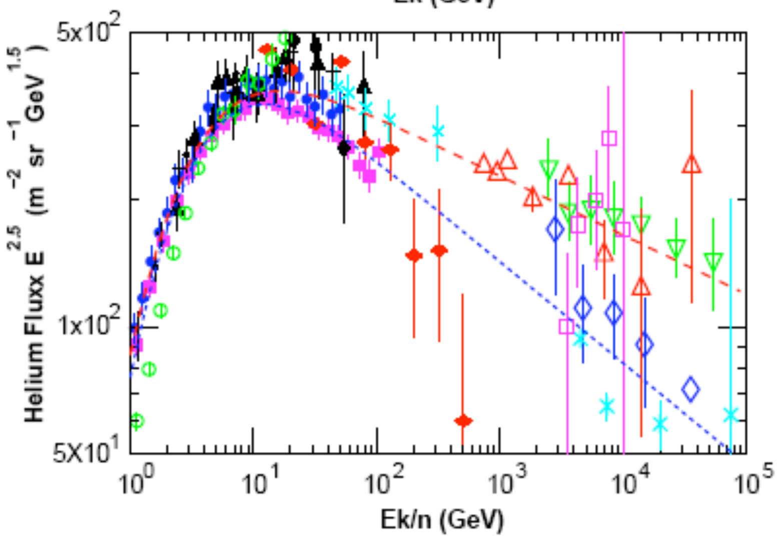
$$r_L = \left(\frac{pc}{Ze}\right)\frac{1}{Bc}$$

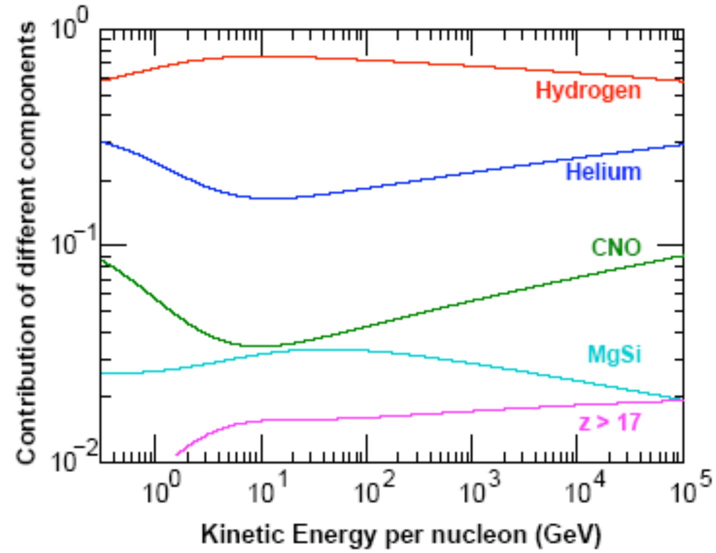
Particles with different charges and masses have the same dynamics in a magnetic field if they have the same rigidity
$R = (A/Z)(m_p\,\gamma vc/e)$ and $m = Am_p$
The lower the rigidity of a CR particle the smaller the prob of reaching the Earth through the heliosphere (very deflected by solar fields)

Composition vs energy

Some of the differences are explained as a result of Spallation = primaries







$$F(E_k) = K\left[E_k + B\exp\left(-\frac{C}{\sqrt{E_k}}\right)\right]^{-\alpha}$$

Energy Spectrum

$$\phi(E) \simeq K\ E^{-\alpha} \qquad \alpha \simeq 2.7$$

KNEE (steepening of the Spectrum) α: $2.7 \to 3$

ANKLE (hardening of the spectrum) α: $3 \to 2$–2.7

$$E_{\mathrm{Knee}} \simeq 3 \times 10^{15}\ \mathrm{eV}$$

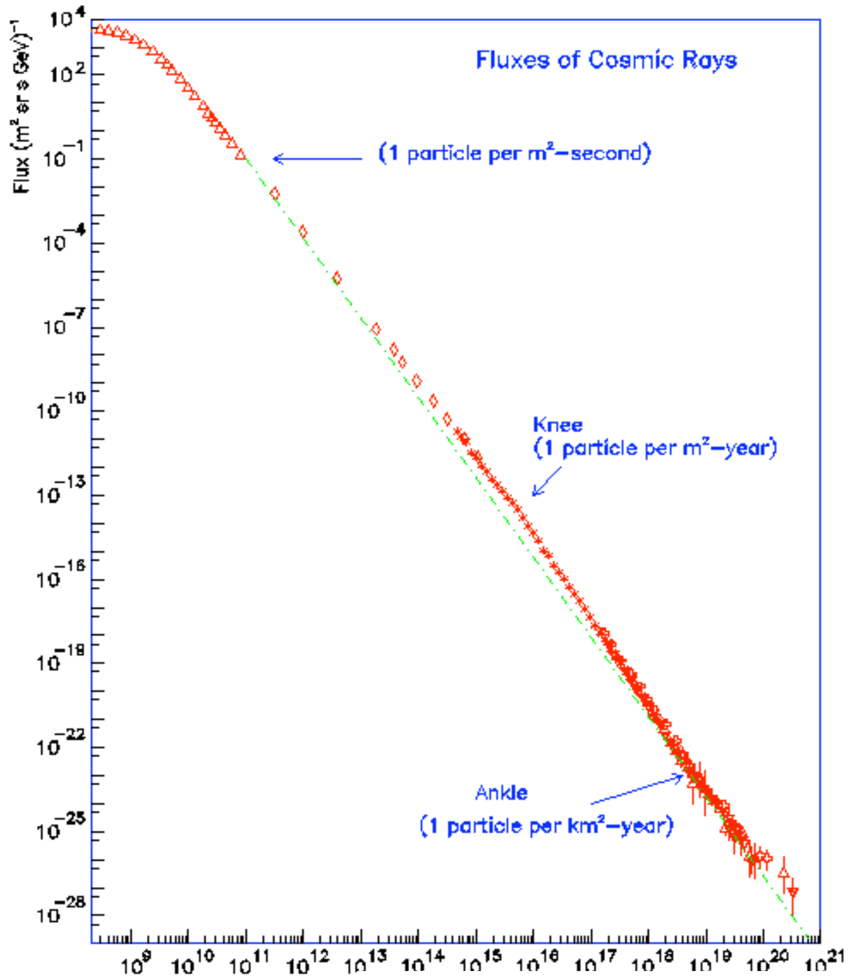
$$E_{\mathrm{Ankle}} \simeq 10^{19}\ \mathrm{eV}$$

$$\frac{dN}{d(\log E)}(1GeV) \approx 10^{3}\ particles/(m^{2}ssr)$$

A 1 m^2 detector counts 10^3 particle/s

$$\frac{dN}{d(\log E)}(10^{19}eV) \approx 10^{-24}\ particles/(m^{2}ssr)$$

A 1 km^2 detector counts 1 particle/year



Energy (eV)/particle

Energy Spectrum

Notice $$\frac{dN}{d(\ln E)} = E\frac{dN}{dE} = AE^{-1.7}$$

By how much the value of the flux is reduced in an energy decade?

$$\Delta \log_{10} E = 1$$

$$\frac{dN}{d(\log_{10} E)} = A' E^{-1.7} \Rightarrow \log_{10} \frac{dN}{d(\log_{10} E)} = \log_{10} A' - 1.7 \log_{10} E \Rightarrow$$

$$\Delta \log_{10} \frac{dN}{d(\log_{10} E)} = -1.7 \Delta \log_{10} E = -1.7 \Rightarrow \log_{10} \Phi_2 - \log_{10} \Phi_1 = \log_{10} \frac{\Phi_2}{\Phi_1} = -1.7 \Rightarrow$$

$$\frac{\Phi_2}{\Phi_1} = 10^{-1.7} = 2 \cdot 10^{-2}$$

About 2 orders of magnitude are lost per decade!

Energy Spectrum

CR energies are laboratory energies

The corresponding CM energy is

$$E_{CM}^2 = s = (p_1 + p_2)^2 = m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2\cos\theta)$$

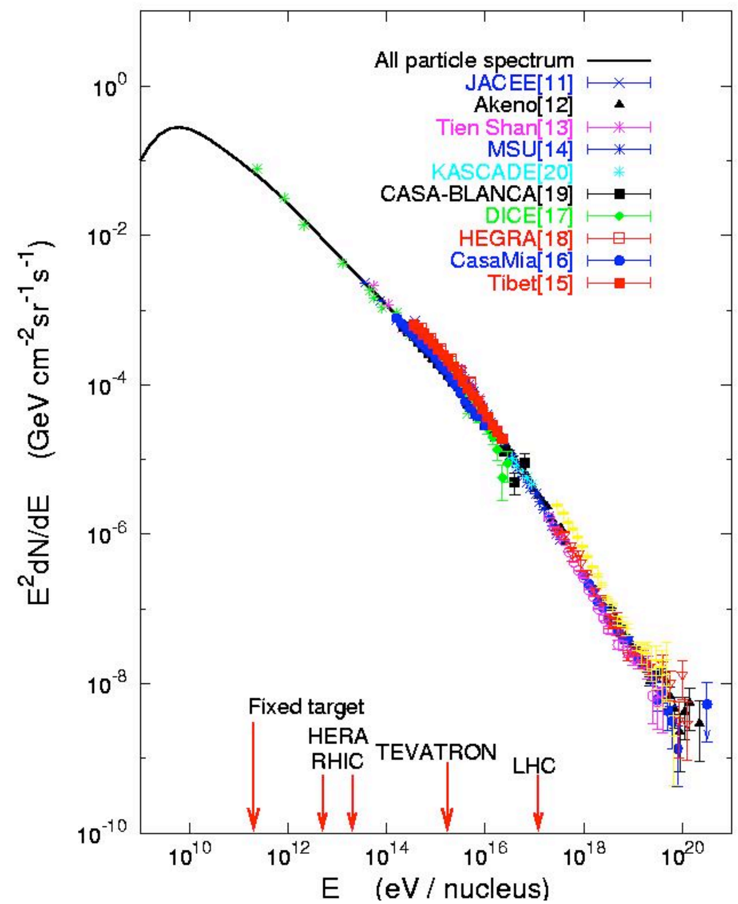
If masses are small compared to energies and the nuclei hit by the CR is at rest:

$$E_{CM}^2 = 2E_1M = 2ME_{Lab}$$

LHC E_{CM} = 14 TeV

M = 1 GeV ⇒ $E_{lab} = 10^{17}$ eV

Spectral Energy Distribution



Kinetic energy per nucleus

E/particle or E/nucleon

Fragmentation of nuclei conserve the energy per nucleons: in spallation processes, when a relativistic CR nuclei during propagation interacts on a proton

$$A + p \rightarrow A_1 + A_2$$

the energy per nucleon is roughly conserved (E_0 energy/nucleon)

$$E_{tot}(A) = A\, E_0$$

$$E_{tot}(A_1) = A_1\, E_0 \qquad\qquad E_{tot}(A_2) = A_2\, E_0$$

Superposition principle: a nucleus of mass number A and energy E is considered as A independent nucleons of energy E/A

E/particle or E/nucleon

For E> 100 GeV the difference between $E_{tot} = E_k + m_p$ ($m_p = 0.938$ GeV) is negligible. Fluxes are often presented as particles per energy per nucleus.

But for E<100 GeV the difference is important and it is common to present nucleons per kinetic energy per nucleon. This is the usual way of presenting the spectrum for nuclei with different masses: the conversion in energy per nucleus is not trivial.

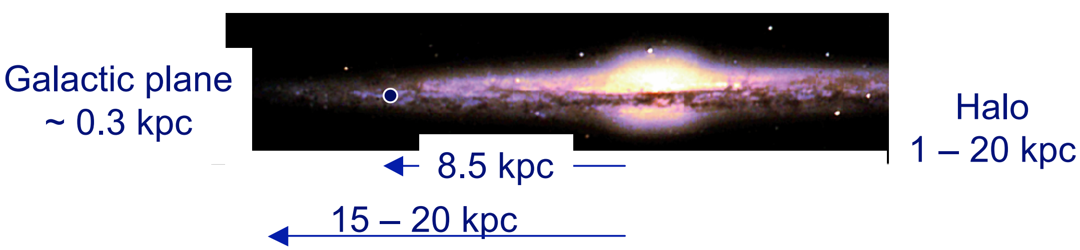
Production of secondary cosmic rays in the atmosphere depends on the intensity of nucleons per energy-per-nucleon independently of whether the incident nucleons are free protons or bound in nuclei

Next Lecture:

Prof. Ellen Zweibel on acceleration mechanisms (Fermi) and some propagation

CRs in the Galaxy

They are the product of stellar reactions and collapses: the main sources of CRs up to the knee are galactic SNRs though the high energy ones could be produced also by extragalactic sources (eg GRBs) Once accelerated by SN shocks they propagate through the ISM that contains matter, magnetic fields and radiation fields that are targets for CR interactions. By the time they reach the solar system they have no memory of the position of their sources. Observations show that CRs at Earth are isotropic to a very large degree, except perhaps the high energy ones. The electrons interact with magnetic and radiation fields and produce synchrotron radiation and in radiation fields boost γ-rays with IC



Interstellar Matter

Most of the ISM consists of hydrogen in the form of atomic neutral hydrogen (HI) and molecular hydrogen H_2. About 10% is He and heavier nuclei.
Atomic H is detected by its 21 cm emission line at radio frequencies and it has a density of about 1 atom/cm^3. The shape of HI distribution has an height in the inner Galaxy of 0.1-0.15 kpc that increases in the outer Galaxy. The density decreases by factors 2-3 in the space between arms of luminous matter.
Molecular H is concentrated especially close to the galactic centre and within solar circle where the density is $n(H_2) \sim 1$ cm^{-3}. The total masses are estimated to be $m(HI) = 5 \times 10^9\ M_{sun}$ and $m(H_2)=0.9\text{-}1.4 \times 10^9\ M_{sun}$.
The extract structure of the magnetic field is not well known: in the vicinity of the solar system B ~ 2 μG. Estimates of the average field strength in the Galaxy are 3-6 μG. For an average field of 3 μG the energy density of the field is $B^2/8\pi = 4 \times 10^{-13}$ erg/cm^3 ~ 0.25 eV/cm^3. The ionized gas and the magnetic field form a magnetohydrodynamic fluid with which CRs interact. Hence the CR energy density should be of the same order. The CR energy density (90% of the energy is carried by < 50 GeV particles)

$$P_{CR} = \rho_{E,CR} = \frac{4\pi}{c}\int E\,\frac{dN}{dE}\,dE \sim 10^{-12}\ \mathrm{erg/cm^3}$$

The transport equation

$Q_j(E,t)$ = source term = number of particles of type j produced and accelerated per cm^3 at time t with energy between E, E+dE in a given location in the Galaxy

These particles diffuse in the Galaxy and their number changes due to the following processes:

1) CR diffusion governed by the diffusion coefficient $K = \beta c \lambda/3$ where λ is the mean diffusion path and $v = \beta c$ the particle velocity
2) CR convection
3) Rate of change of particle energy dE/dt (positive for reacceleration processes, negative for energy losses)
4) Particle loss term due to interactions or decays
5) Particle gain term: particles of type i may produce particles of type j

The propagation can be described in the Leaky Box approximation: a volume, where particles freely propagate they have an escape probability P_{esc} and the mean amount of matter traversed λ_{esc} by the CRs in the Galaxy before they escape it is

$$\lambda_{esc} = \rho_{ISM} \beta c \tau_{esc}$$

where ρ_{ISM} is the average matter density~1 cm^{-3} and τ_{esc} is the lifetime of CRs in the Galaxy.

The transport equation

A simplified equation for stable CR nuclei (neglecting energy losses and gains and assuming an equilibrium CR density)

$$\frac{N_j(E)}{\tau^j_{esc}(E)} = Q_j(E) - \frac{\beta c \rho_{ISM}}{\lambda_j(E)} N_j(E) + \frac{\beta c \rho_{ISM}}{m} \sum_{i>j} \sigma_{i\to j} N_i(E)$$

1)

4) Number of particles of type j lost in propagation due to fragmentation

5)Sum over all higher mass nuclei that produce j in spallation. m =particle mass

The observed CR composition can be explained in terms of the general elemental abundance + fragmentation cross section if they have traversed on average 5-10 g/cm^2. Hence for ρ_{ISM} ~1 cm^{-3} the escape time is

$\tau_{esc} = N_A \lambda_{esc}/c \sim 3\times10^6$ yrs

In reality the containment time depends on the energy (it is rigidity dependent) as (true for R>4 GV)

$$\lambda_{esc} \propto \beta \left(\frac{4}{R}\right)^{\delta} g/cm^2$$

where R is the particle rigidity in GV and $\delta \sim 0.6$.

A suitable isotope to measure τ_{esc} is ^{10}Be with a 1/2 life of 1.6 x 10^6 yrs. Its flux can be compared to that of the stable isotopes ^{9}Be and ^{7}Be. The production of the 3 isotopes depends on the production cross section and on λ_{esc} so that $\tau_{esc} \approx$ 8-30 x 10^6 yrs for which ρ_{ISM} ~0.2-0.3 cm^{-3} < matter density in the disc.

The transport equation

With the further simplification that no CR nuclei are created in propagation

$$\frac{N_j(E)}{\tau_{esc}^j(E)} = Q_j(E) - \frac{\beta c \rho_{ISM}}{\lambda_{\text{int}}^j(E)} N_j(E) \Rightarrow N_j(E) = \frac{Q_j(E)}{\left(\frac{1}{\tau_{esc}^j(E)} + \frac{\beta c \rho_{ISM}}{\lambda_{\text{int}}^j}\right)}$$

while λ_{esc} is the same for all nuclei with the same rigidity R, λ_{int} depends on the mass of the nucleus (for a p it is about 50.8 g/cm^2 at low energy, for C it is 6.4 g/cm^2 and for Fe it is 2.6 g/cm^2)

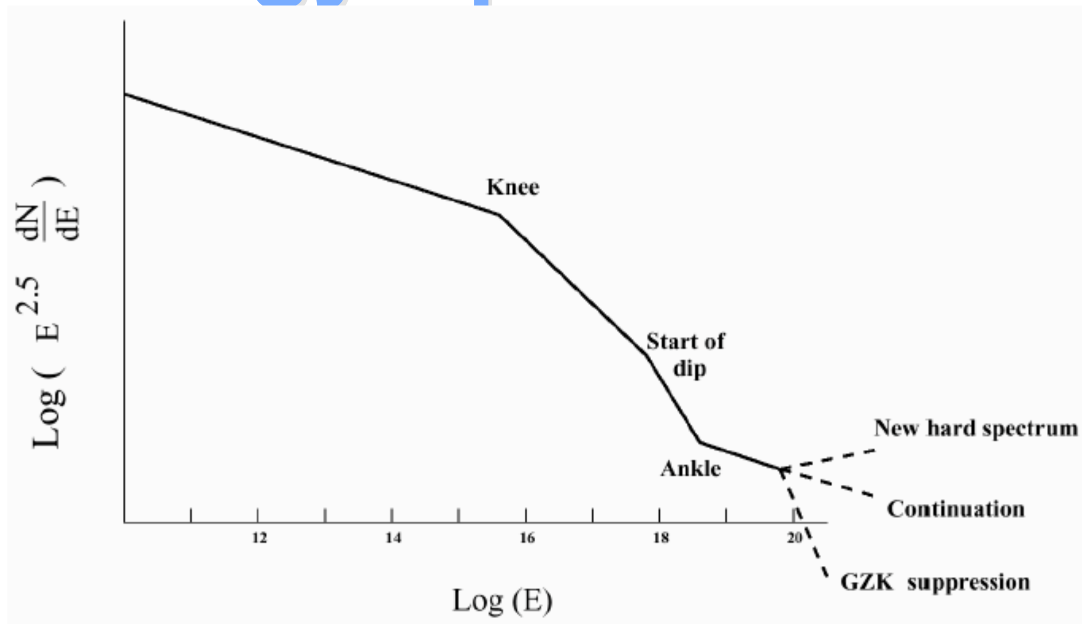
This equation suggests that at low energies the energy spectra for different nuclei will be different and will become asymptotically parallel to each other at high energy if they were accelerated to the same spectral index at the source

The smaller λ_{int} the bigger the modification respect to the source spectrum.

For protons λ_{esc} (10 g/cm^2) is always smaller than λ_{int} and the modification to the spectrum from $E^{-\alpha}$ at acceleration to $E^{-(\alpha+\delta)}$ after propagation. So if the acceleration spectrum is $E^{-2.1}$ we obtain the $E^{-2.7}$ observed spectrum for $\delta = 0.6$.

$$\tau_{esc}(E)\, Q_{source}(E) \;\propto\; \frac{dN}{dE}_{observed} \;\propto\; E^{-\alpha}.$$

Features of energy Spectrum



$$\phi(E) \simeq K\ E^{-\alpha} \qquad \alpha \simeq 2.7$$

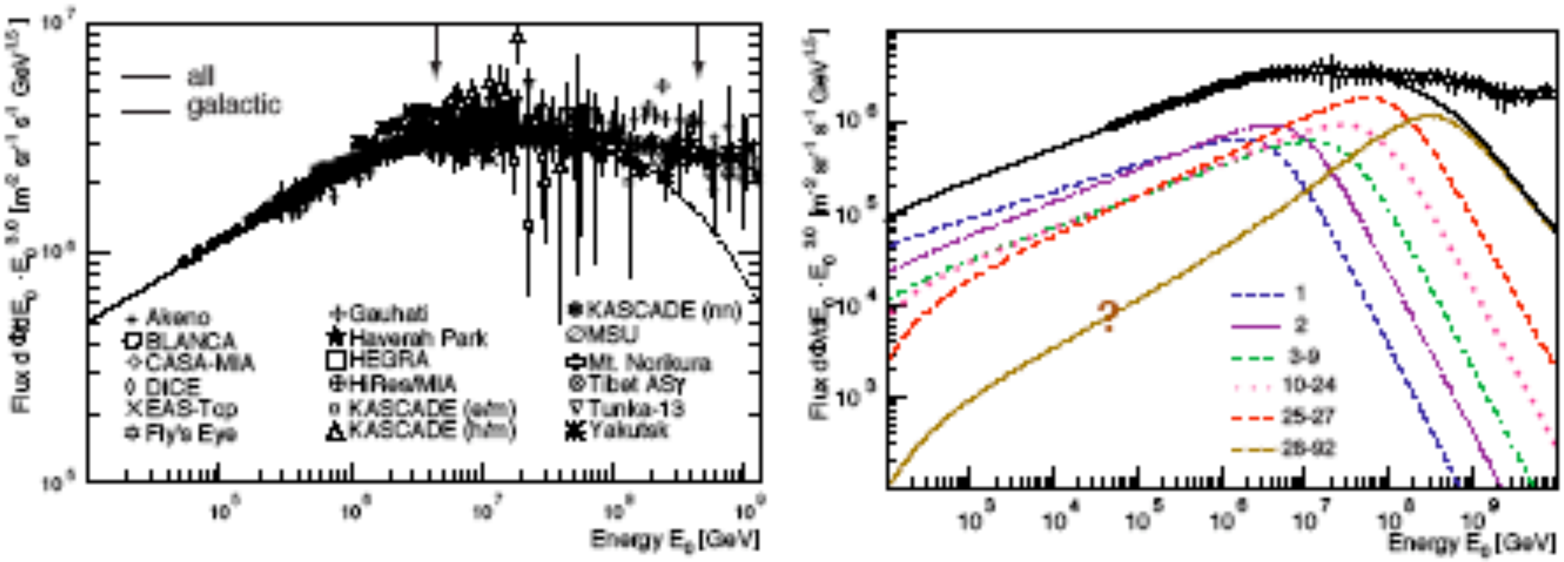
KNEE (steepening of the Spectrum) α: $2.7 \to 3$

ANKLE (hardening of the spectrum) α: $3 \to 2$–2.7

$$E_{\rm Knee} \simeq 3 \times 10^{15}\ {\rm eV}$$

$$E_{\rm Ankle} \simeq 10^{19}\ {\rm eV}$$

The first and second knee

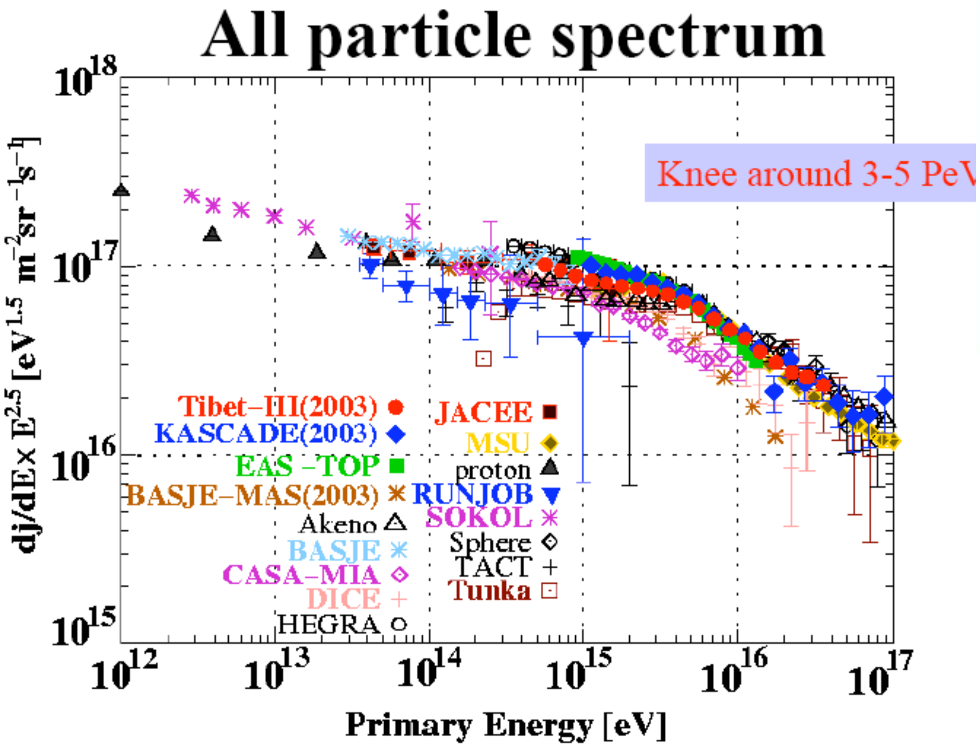


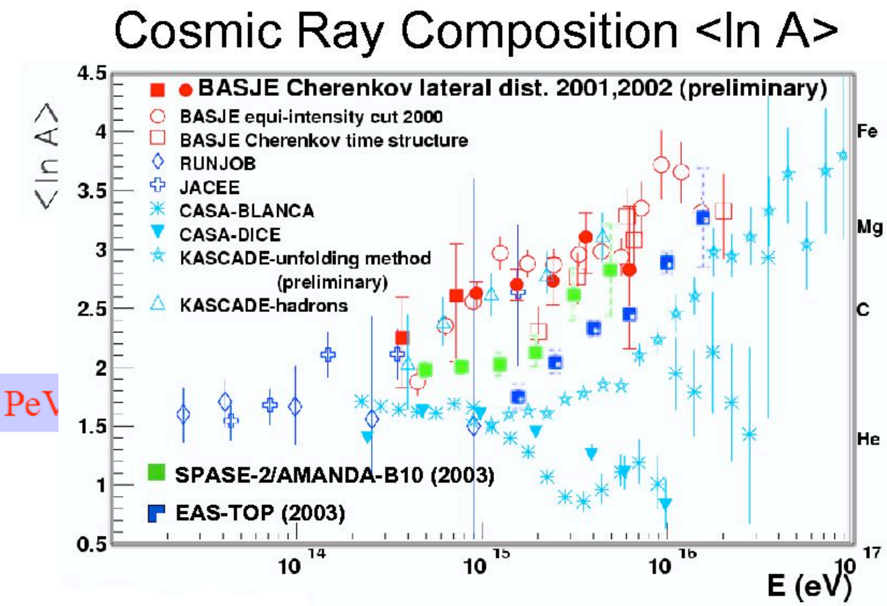
Left) All particle spectra normalized (±10%) for different experiments. Arrows indicate the first knee at E_k = 4.5 PeV and the second knee at 400 ~PeV.

Right) The average flux of the measurements on the left (points) and spectra for various elemental groups with the indicated charge number range according to a parametrization of the measurements. ? Indicates a proposed contribution of Z>26 elements extrapolated from low energy measurements

- $E_{max} \sim \beta_{shock}$ Ze x B x R_{shock} (due to finite lifetime of the shock front)
  - → E_{max} ~ Z x 0.1-5 PeV with exponential cutoff of each component
  - But spectrum continues to higher energy:
    - → E_{max} problem

The knee


All particle spectrum
Knee around 3-5 PeV
dj/dE× E^2.5 [eV^1.5 m^-2 sr^-1 s^-1]
Primary Energy [eV]
Tibet–III(2003)
KASCADE(2003)
EAS –TOP
BASJE–MAS(2003)
Akeno
BASJE
CASA–MIA
DICE
HEGRA
JACEE
MSU
proton
RUNJOB
SOKOL
Sphere
TACT
Tunka

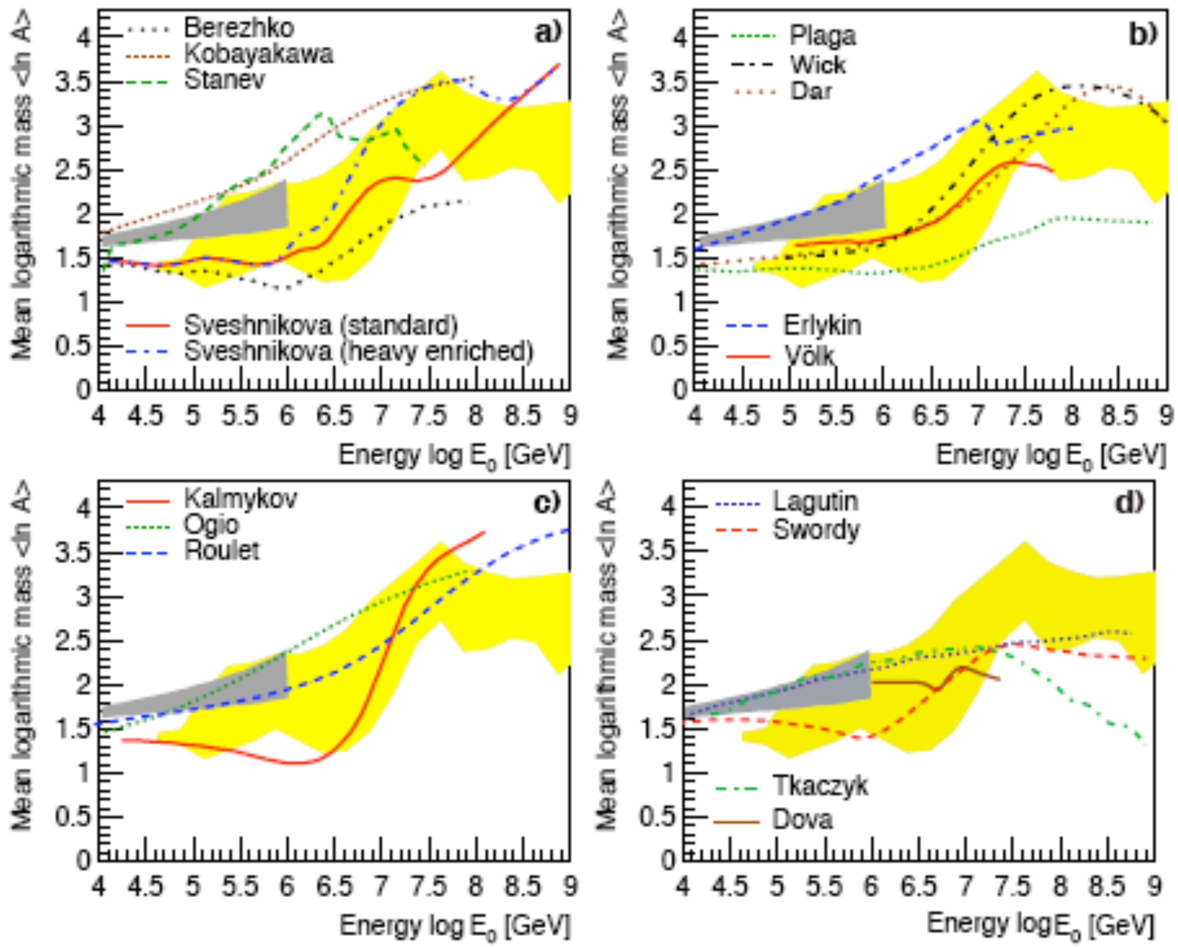

Cosmic Ray Composition <ln A>
<ln A>
BASJE Cherenkov lateral dist. 2001,2002 (preliminary)
BASJE equi-intensity cut 2000
BASJE Cherenkov time structure
RUNJOB
JACEE
CASA-BLANCA
CASA-DICE
KASCADE-unfolding method (preliminary)
KASCADE-hadrons
SPASE-2/AMANDA-B10 (2003)
EAS-TOP (2003)
Fe
Mg
C
He
E (eV)

Possible models

Acceleration in SNRs

acceleration in GRBs, …

Diffusion
In the
Galaxy



Propagation
In the Galaxy
As well as
Interactions
With
background
γs and νs

Fig. 7. Mean logarithmic mass as function of energy obtained by direct observations (dark grey area) and air shower experiments (light grey area) compared with different models (lines). a) Acceleration in SNRs[20,22,21,23]; b) acceleration in GRBs[49,24,25], single source model[50], reacceleration in the galactic wind[51]; c) diffusion in Galaxy[40,52,53]; d) propagation in the Galaxy[54,34], as well as interaction with background photons[55] and neutrinos[56]. For details see[57].