Energetic particle transport in the magnetosphere and atmosphere

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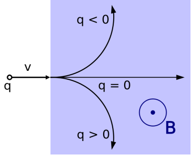
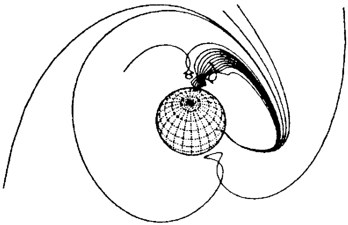
Motivation

- Understand the high-energy processes at the Sun that accelerate particles to cosmic ray energies
- For this task cosmic ray measurements in space and on Earth are used
- For the interpretation of ground based detectors the transport in the magnetosphere and in the atmosphere must be known

Transport in the Geomagnetosphere

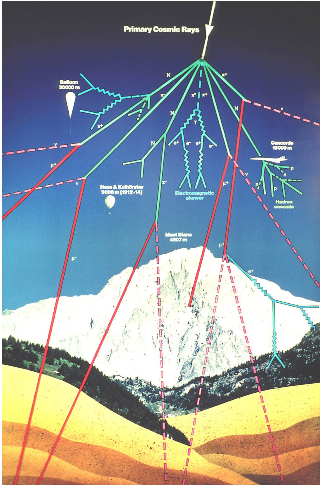
- Moving charged particles are deviated in magnetic fields (Lorentz Force)
- Positive particles deflect one way and negative particles the other way
- Charged particles entering the Earth magnetic field describes complex trajectories
- Charged particles must have a minimal energy to reach the top of the Earth's atmosphere





Transport in the Atmosphere

- Interactions of primary cosmic rays with electrons and nuclei of atoms and molecules in atmosphere
- As a result composition of radiation changes (secondary cosmic rays)
- All particles suffer energy losses through hadronic and/or electromagnetic processes.



Nomenclature and defintions I

Energy unit:

$$1\,\text{eV} = 1.6 \cdot 10^{-19}\,\text{J}$$

1 electron Volt (eV) is the kinetic energy a particle with charge *e* gains by being accelerated through a potential difference of 1 Volt.

keV (10^3eV), MeV (10^6eV), GeV (10^9eV)

Total energy of a particle, E_T:

$$E_T = E_{kin} + m_0 c^2 = mc^2 = \gamma m_0 c^2$$

E_{kin}:	kinetic energy
m_0:	rest mass
c:	speed of light
γ:	Lorentz factor, $\gamma = \frac{1}{\sqrt{1-(\frac{v}{c})^2}}$

Rest mass of nucleons:

$$m_p = 938.272\,\text{MeV}/c^2$$
$$m_n = 939.565\,\text{MeV}/c^2$$

Nomenclature and defintions II

E_T is related to the particle momentum, p, by

$$E_T = \sqrt{p^2c^2 + m_0^2c^4}$$

Magnetic rigidity, R

$$R = \frac{p \cdot c}{Z \cdot e}$$

where $Z \cdot e$ is the charge of the particle.

Unit of R is Volt. Convinient units are MV (10^6V), GV (10^9V)

The rigidity of a particle is a measure of its resistance to a magnetic force.

Paritcles with the same rigidity, charge sign and initial conditions have identical trajectories in a static magnetic field.

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Nomenclature and defintions III

Conversion from kinetic energy per nucleon, E_A, to rigidity, R

$$R = \frac{A}{Z}\sqrt{(\gamma^2 - 1)} \cdot E_{0A}$$

where A is the atomic number, Z is the atomic charge, γ is the Lorentz factor, and E_{0A} is the rest mass energy per nucleon.

Computation of the Lorentz factor, γ

from either the cosmic ray kinetic energy per nucleon, E_A:

$$\gamma = \frac{E_A + E_{0A}}{E_{0A}}$$

or from the cosmic ray rigidity, R:

$$\gamma = \sqrt{(\frac{R \cdot Z}{A/E_{0A}})^2 + 1}$$

Conversion rigidity $\longleftrightarrow$ kinetic energy for protons

Conversion kinetic energy to rigidity for proton:

$$R = \sqrt{(E_{kin} + E_0)^2 - {E_0}^2}$$

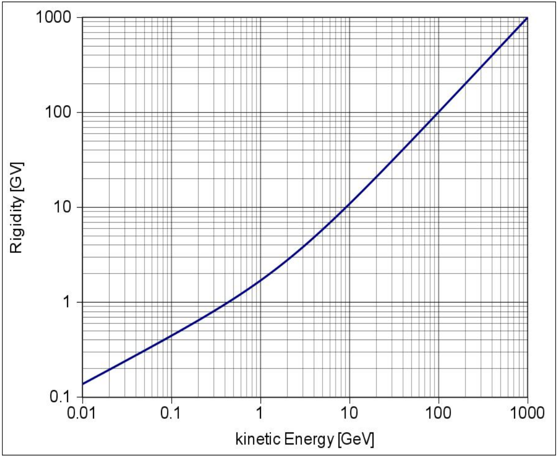
where

- R: rigidity in [MV]
- E_{kin}: kinetic energy of proton in [MeV]
- E_0: rest mass of proton, $E_0 = 938.27$ MeV

Conversion rigidity to kinetic energy, E_{kin}, of a proton:

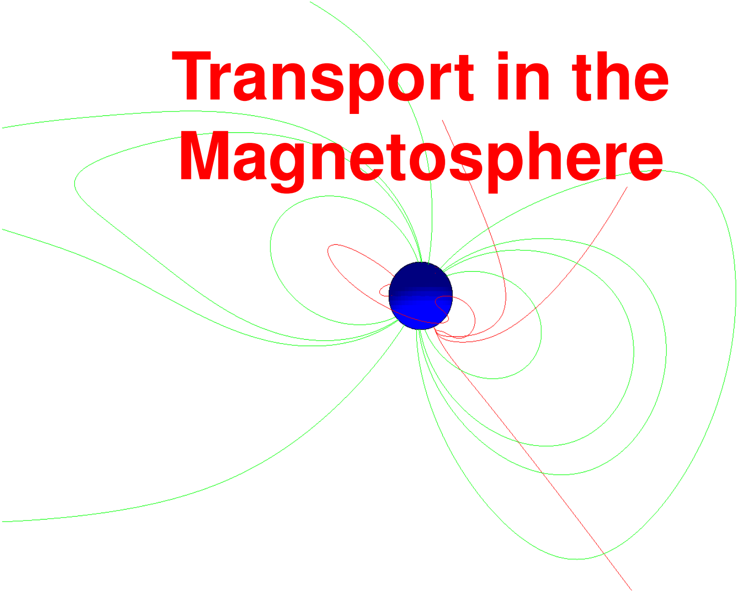
$$E_{kin} = \sqrt{R^2 + E_0^2} - E_0$$

Rigidity vs. kinetic energy for protons



1 GV $\hat{=}$ $\sim$450 MeV

Transport in the Magnetosphere



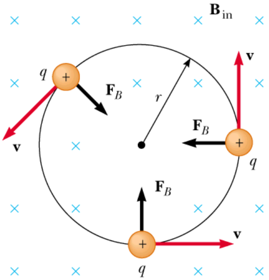
Motion of charged particles in static and uniform magnetic field I

Lorentz force:

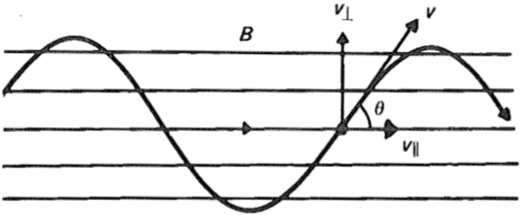
$$\vec{F} = q \cdot \vec{E} + q \cdot \vec{v} \times \vec{B}$$

Cyclotron radius:

$$\vec{r}_{cy} = \frac{m}{Z \cdot e} \frac{\vec{B} \times \vec{v}}{B^2}$$



Motion of charged particles in static and uniform magnetic field II



$\vec{B}$:	uniform magnetic field
$\vec{v}$:	speed of particle
$v_{\|\|}$:	speed rectangular to $\vec{B}$
$v_\perp$:	speed parallel to $\vec{B}$
θ:	pitch angle, i.e. angle between $\vec{v}$ and $\vec{B}$

Magnetic fields

Units:

1 Gauss [G] = 100 000 Nanotesla [nT] = 10^5 nT

1 Gamma [γ] = 1 Nanotesla [nT] $\qquad 1\ \mathrm{T} = 1\,\frac{\mathrm{Vs}}{\mathrm{m}^2}$

Interplanetary magnetic field near Earth:

typical $B_{IMF} \approx 5\,\mathrm{nT}$

Earth magnetic field at ground:

$B_{equator} \sim 0.3\ Gauss = 30'000\,\mathrm{nT}$

$B_{pole} \sim 0.6\ Gauss = 60'000\,\mathrm{nT}$

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Cyclotron radius

Interplanetary magnetic field near Earth:

$$r_{cy}[AU] = \frac{R[V]}{4.5 \cdot 10^{10} \cdot B[nT]}$$

B = 5 nT, R = 1.0 GV $\rightarrow$ r_{cy}= 0.005 AU

Earth magnetic field at ground:

$$r_{cy}[cm] = \frac{R[V]}{300 \cdot B[gauss]}$$

B = 0.3 gauss, R = 1.0 GV $\rightarrow$ r_{cy} = 110 km $\hat{=}$ 0.02 Re

Charged particle equation of motion in a magnetic field

$$\gamma m_0 \dot{\vec{v}} = q \cdot (\vec{v} \times \vec{B})$$

where

$\dot{\vec{v}}$	particle acceleration
q	charge of particle
m_0	particle's mass at rest
$\vec{v}$	particle velocity
$\vec{B}$	magnetic field vector

Determination of cosmic ray particle trajectories:
Numeric integration of the equation of motion

Charged particle equation of motion in a magnetic field

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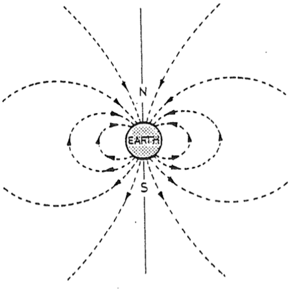
Determination of cosmic ray particle trajectories:
Numeric integration of the equation of motion

Earth magnetic field I

First approach: Description of the Earth magnetic field by a geocentric magnetic dipole

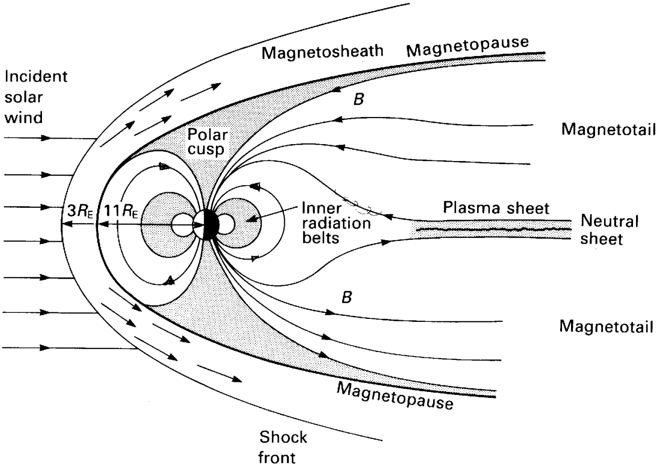


$$|\vec{B}| = \frac{M}{r^3} \cdot \sqrt{1 + 3\sin\lambda^2} \propto \frac{1}{r^3}$$

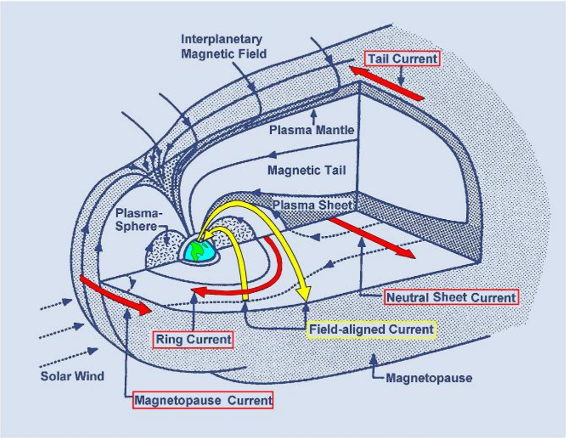
where

M	geomagnetic moment ($M = 8.1 \cdot 10^{25}$ Gauss cm^3),
r	radial distance from Earth's center,
λ	geomagnetic latitude

Earth magnetic field II



Earth magnetic field III: Magnetospheric currents



$$B \propto \frac{I}{r}$$

Earth magnetic field IV: Magnetic field models

- Main field generated by sources in the Earth's interior:

  International Geomagnetic Reference Field (IGRF)

  International Union of Geodesy and Geophysics (IUGG) /
  International Association of Geomagnetism and Aeronomy (IAGA)

- Magnetic field generated by current systems:

  Tsyganenko89, Tsyganenko96, Tsyganenko2001

Earth magnetic field V: IGRF

- The IGRF model is a Gauss spherical harmonic model that describes Earth's main magnetic field and its secular variation

- Gauss coefficients are derived from magnetic field measurements (geomagnetic stations, magnetometers on ships, and satellite measurements)

- Every 5 years a new set of Gauss coefficients g_n^m and h_n^m are published by International Association of Geomagnetism and Aeronomy (IAGA)

- The 12th Generation IGRF will accept dates in the range 1900 to 2025

Earth magnetic field VI: External magnetospheric field model

The Tsyganenko89 model provides 7 states of the magnetosphere corresponding to different levels of geomagnetic activity

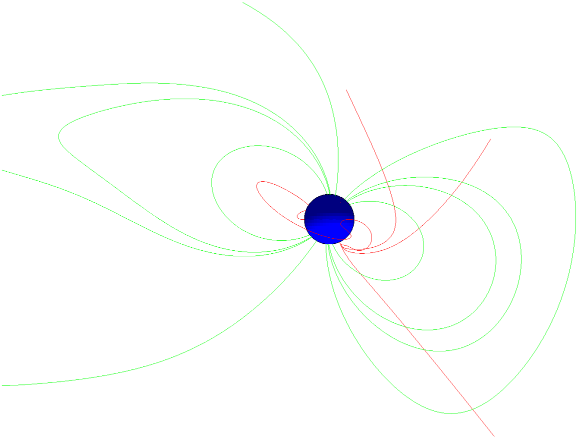
The different states, *Iopt*, are described by the K_p-index as follow:

Iopt	1	2	3	4	5	6	7
K_p	0,0+	1-,1,1+	2-,2,2+	3-,3,3+	4-,4,4+	5-,5,5+	$>$6-

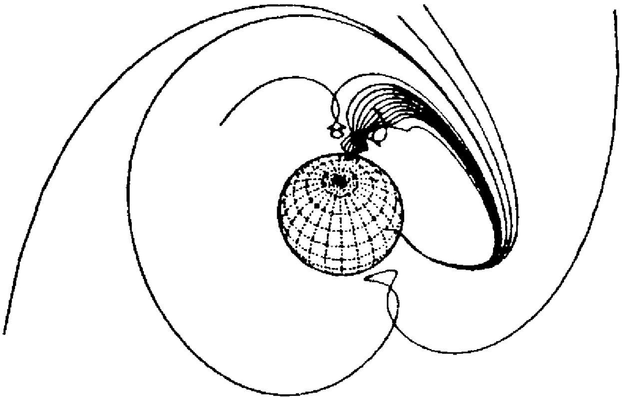
Trajectory computation: Solution method

- Determination of trajectories by numeric integration of the equation of motion by using a geomagnetic field model.
- Path of a negative charged particle with rigidity, R, is identical to path of a positive charged particle but with reverse sign of the velocity vector.
- Trajectory is computed in the reverse direction, i.e. starting point = above the observation location (20 km asl).
- Vertical incidence at the top of the atmosphere.

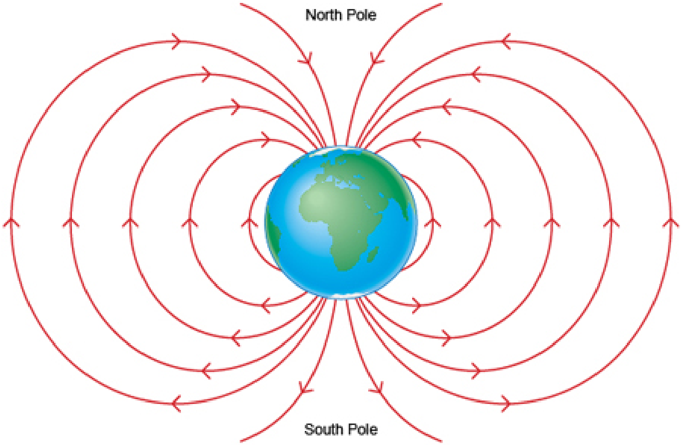
CR particle in Earth's magnetic field



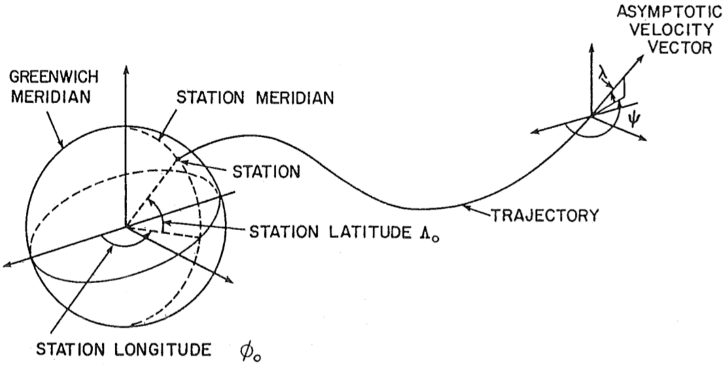
Allowed / forbidden trajectories



Minimal rigidity for access



Definition asymptotic direction



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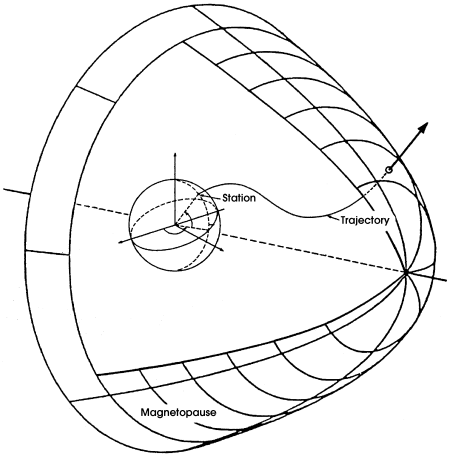
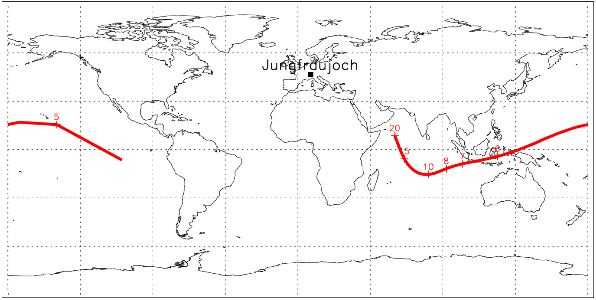


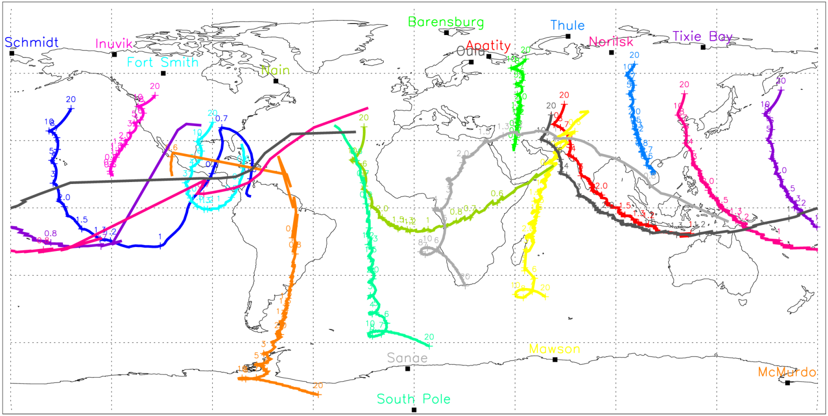
Asymptotic directions for the location Jungfraujoch



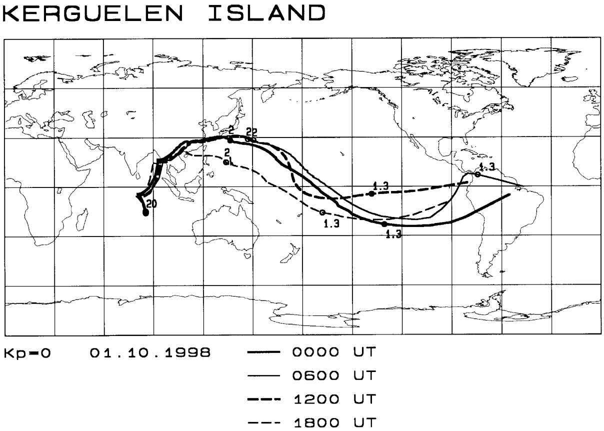
Jungfraujoch:

Geographic latitude:	46.55° N
Geographic longitude:	7.98° E
Altitude:	3570m asl

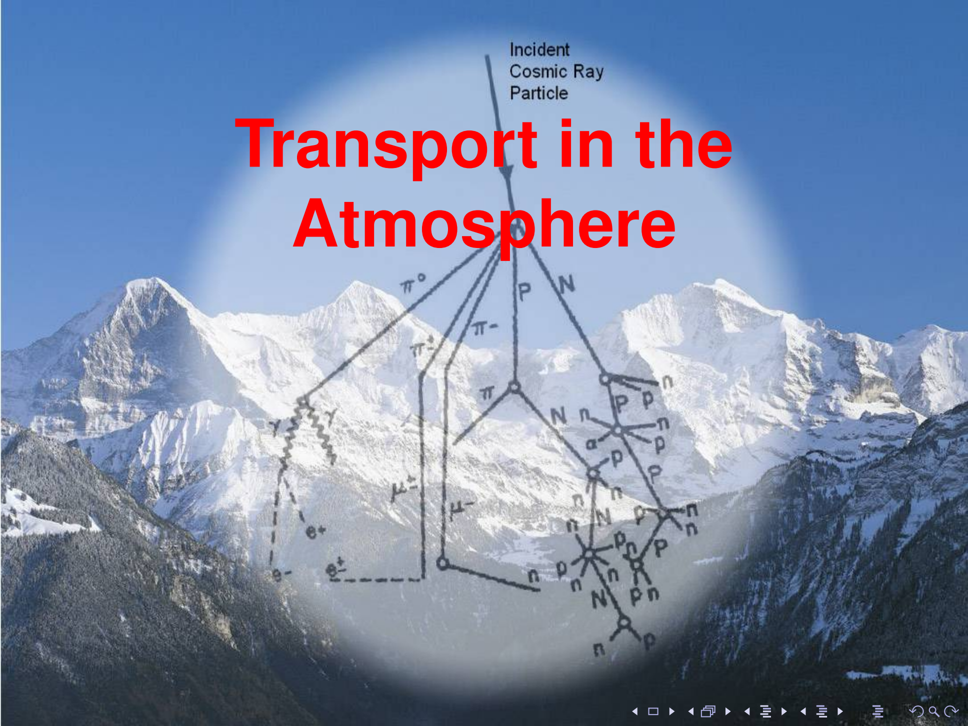
Computed asymptotic directions for polar neutron monitor locations



Asymptotic directions vs. time

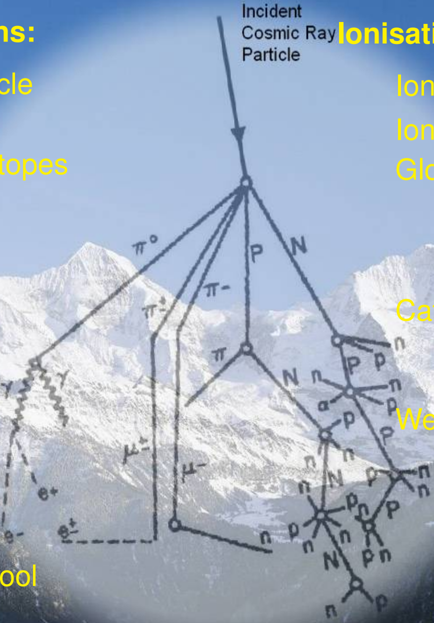


Transport in the Atmosphere



Nuclear interations:

- Secondary particle fluxes, spectra
- Cosmogenic isotopes

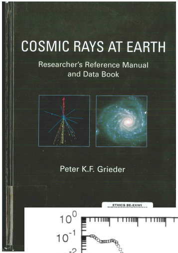


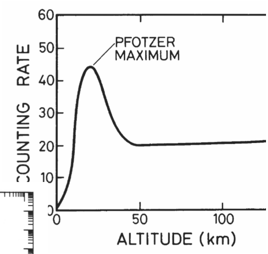
Ionisation:

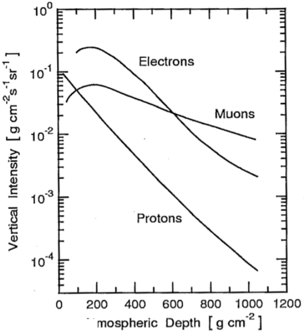
- Ionisation rate
- Ion concentration
- Global electric circuit
  - Commmunication
  - Lightnings, Thunderclouds
- Catalytic Reactions
  - Ozone
  - Nitrates
- Weather and Climate
  - Lightning
  - CR and Clouds

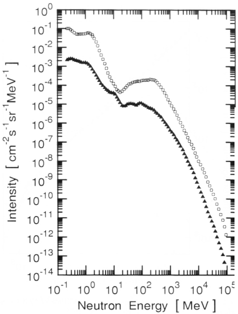
- Radiation effects
- Genetic mutations
- CR as diagnostic tool

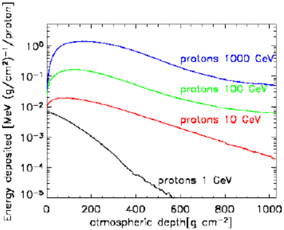
Cosmic Rays in the Earth's atmosphere



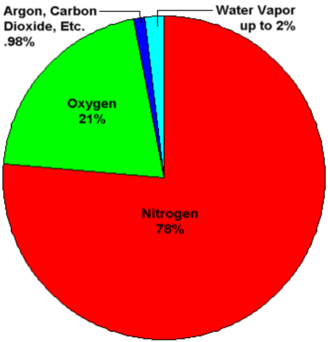






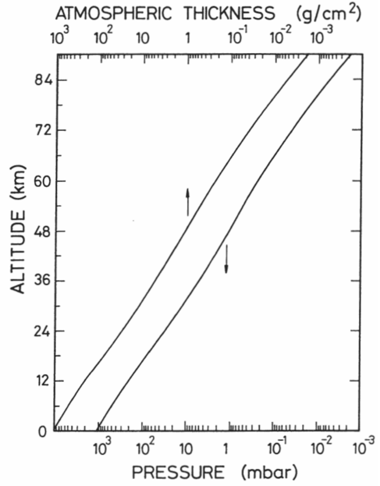


Earth's atmosphere I: Chemical composition



Chemical element	Proportion by Volume
Nitrogen	~ 78 %
Oxygen	~ 21 %
Argon	~ 1 %
...	

Earth's atmosphere II: Atmospheric thickness / atmospheric depth



Atmospheric depth:

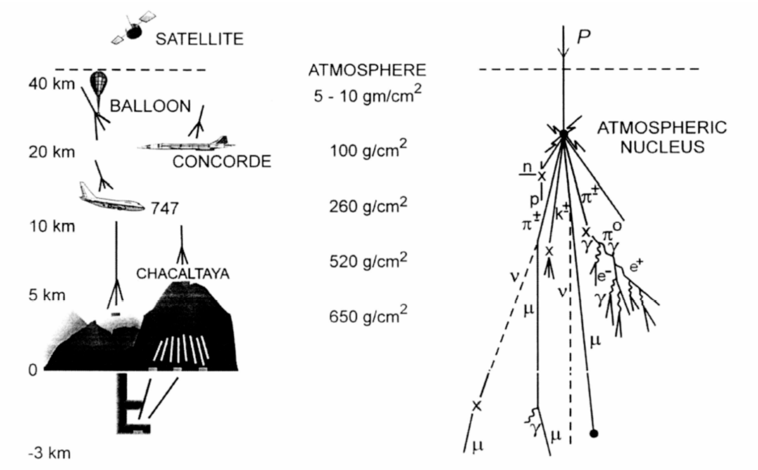
20'000 m asl:	$\sim$50 g $\cdot$ cm^{-2}
11'000 m asl:	$\sim$250 g $\cdot$ cm^{-2}
Sea level:	$\sim$1'033 g $\cdot$ cm^{-2}

1'033 g $\cdot$ cm^{-2} = 1'013 mbar = 760 mmHg

Earth's atmosphere III: Models of Earth's atmosphere

- U.S. Standard Atmosphere
- International Standard Atmosphere (ISA)
- NRLMSISE 2000 model

Cosmic ray cascade in the Earth's atmosphere



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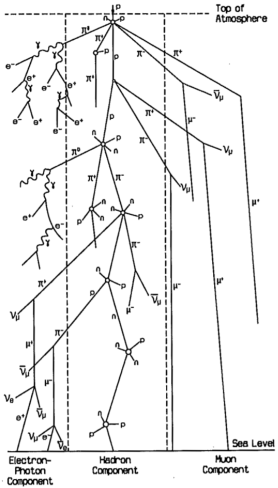


The "standard picture"

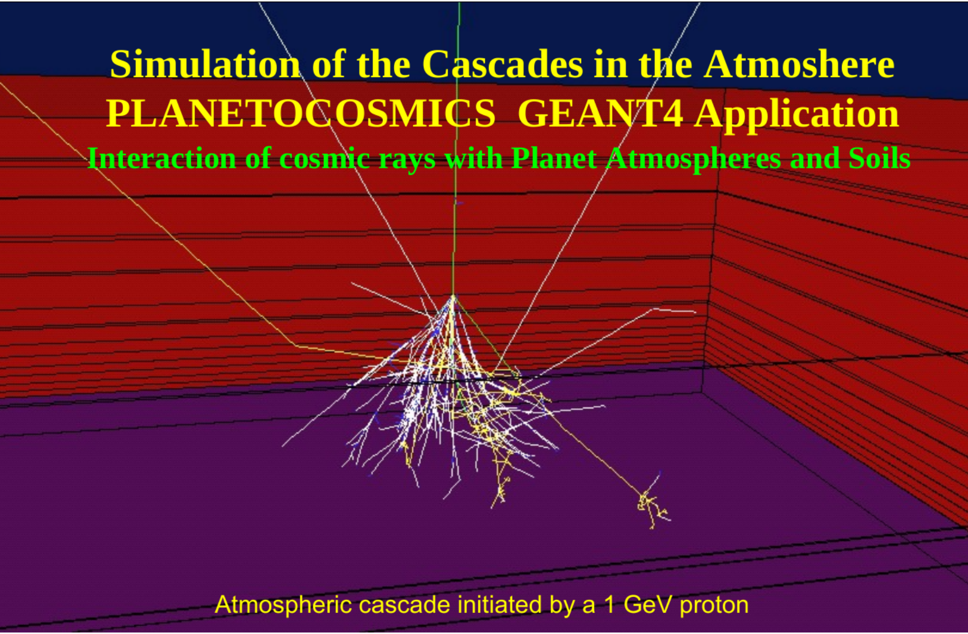
Cosmic ray cascade in the Earth's atmosphere

Present solution to the problem: cascade programs

e.g. PLANETOCOSMICS (GEANT4 application)

Technique:

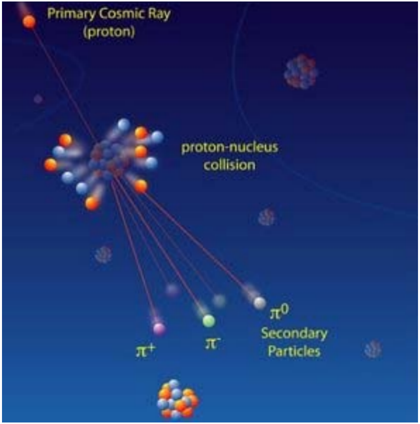
1. calculate $\bar{N}_{kij}^{k_0}(h, R_0, \vartheta)$
   i.e. the number of secondaries of type k, in energy interval $E_i + \Delta E_i$, in zenith angle interval $\vartheta_j + \Delta\vartheta_j$, produced on average at atmospheric depth h by a primary particle of type k_0, penetrating the Earth's atmosphere with rigidity R_0 under a zenith angle ϑ_0
2. take into account cutoff information
3. integrate over respective primary particle spectrum

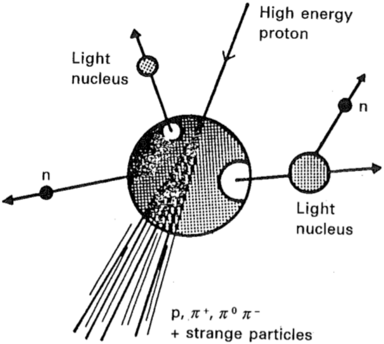

Simulation of the Cascades in the Atmoshere
PLANETOCOSMICS GEANT4 Application
Interaction of cosmic rays with Planet Atmospheres and Soils
Atmospheric cascade initiated by a 1 GeV proton

Basic physics background

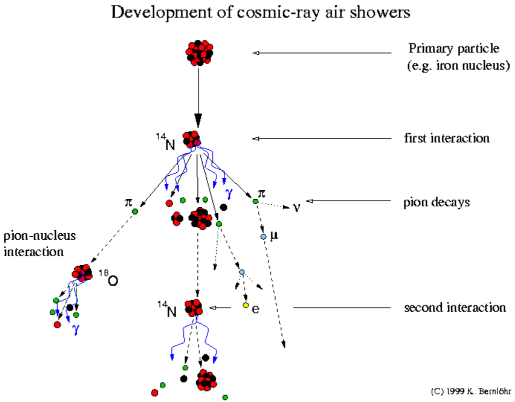
"interaction of particles and radiation with matter"

Nuclear Interactions I



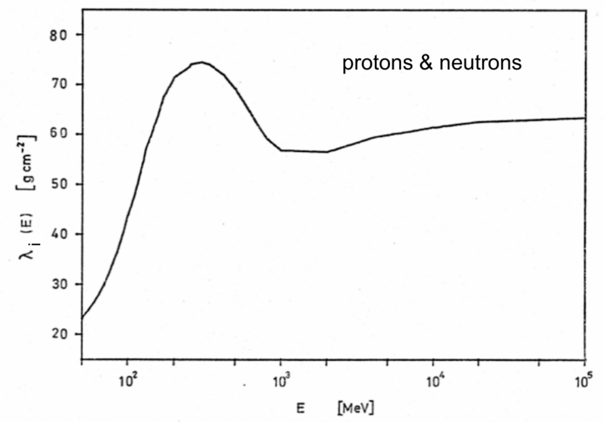


Nuclear Interactions II



Nuclear Interactions III

The hadronic interaction mean free path λ_i (g cm^{-2})



Nuclear Interactions IV: Energy Transport

A hadron having an initial energy E_0,
undergoing n interactions
with a mean inelasticity, $< k >$,
will retain on average an energy, E, of

$$E = E_0 \cdot (1 - < k >)^n$$

typically $< k > \approx 0.5$

Production of Pions & Muons I

Of all the secondaries, pions (π^+, π^-, π^0) are the most abundant

Mass:

$$m_{\pi^0} = 134.97 \text{ MeV/c}^2$$
$$m_{\pi^\pm} = 139.57 \text{ MeV/c}^2$$

Very short mean life times: π^0: $\tau \approx 10^{-16}$ s $\quad \pi^0 \Rightarrow \gamma + \gamma$

$\pi^\pm$: $\tau \approx 2.6 \cdot 10^{-8}$ s

$$\pi^+ \Rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \Rightarrow \mu^- + \bar{\nu}_\mu$$

Decay within meters!

Interaction mean free path in air: ~ 120 g cm^{-2}

Production of Pions & Muons II

Mass: $m_\mu = 105.658\ \text{MeV/c}^2$

Mean lifetime: $\tau \approx 2.197 \cdot 10^{-6}\ \text{s}$

$$\mu^+ \Rightarrow e_+ + \nu_e + \bar{\nu}_\mu$$
$$\mu^- \Rightarrow e_- + \bar{\nu}_e + \nu_\mu$$

Although their lifetime without relativistic effects would allow a half-survival distance of only about 500 m at most, the time dilation effect of special relativity allows cosmic ray secondary muons to survive the flight to the Earth's surface.

Muons

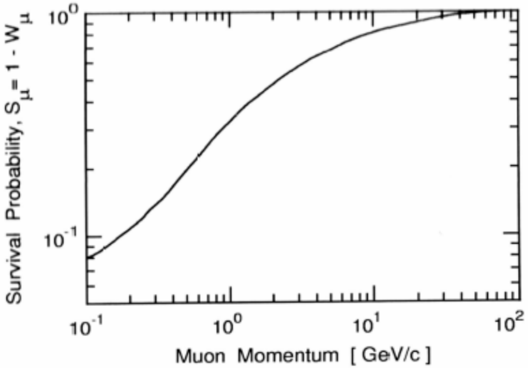


Figure 1.6: Survival probability of muons originating from an atmospheric depth of 100 g/cm^2 to reach sea level, versus muon momentum.

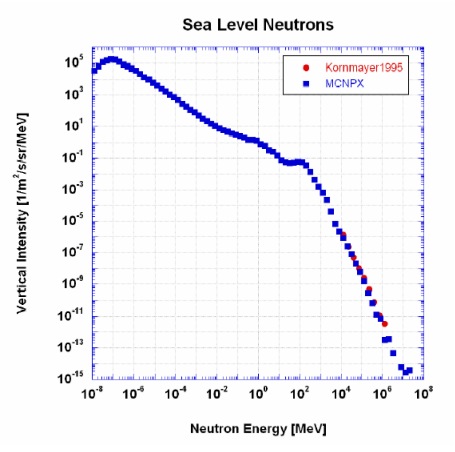
Differential Proton Spectra

Tabelle 9
Differentielles Protonenspektrum in der atmosphärischen Tiefe $h = 1033\ \mathrm{g\,cm^{-2}}$ für mittlere Sonnenaktivität und $\bar{R}_{CV} \approx 4.4$ GV

Kinetische Energie [MeV]	$\Phi_p(E, \vartheta, h = 1033\ \mathrm{g\,cm^{-2}})$ [Protonen/cm² sterad sec MeV] Zenitwinkel 0°–15°	15°–30°	30°–45°	45°–60°	60°–90°
50– 100	0.51E–06	0.39E–06	0.16E–06	0.44E–06	0.66E–07
100– 200	0.19E–06	0.33E–06	0.19E–06	0.18E–06	0.31E–06
200– 400	0.43E–06	0.13E–06	0.83E–07	0.54E–07	0.58E–08
400– 600	0.21E–06	0.59E–07	0.31E–07	0.0	0.76E–08
600– 800	0.12E–06	0.41E–07	0.36E–07	0.19E–07	0.0
800– 1000	0.90E–07	0.32E–07	0.22E–07	0.53E–08	0.0
1000– 1250	0.66E–07	0.59E–07	0.69E–08	0.0	0.0
1250– 1500	0.47E–07	0.17E–07	0.14E–07	0.0	0.0
1500– 1750	0.45E–07	0.41E–07	0.11E–07	0.0	0.0
1750– 2000	0.60E–07	0.26E–07	0.51E–08	0.33E–08	0.0
2000– 3000	0.29E–07	0.13E–07	0.23E–08	0.17E–08	0.0
3000– 5000	0.10E–07	0.19E–08	0.81E–09	0.0	0.0
5000– 7500	0.21E–08	0.0	0.0	0.0	0.0
7500– 10000	0.23E–09	0.11E–08	0.0	0.0	0.0
10000– 15000	0.15E–09	0.0	0.0	0.0	0.0
15000– 20000	0.16E–09	0.0	0.0	0.0	0.0
20000– 30000	0.0	0.0	0.0	0.0	0.0
30000– 40000	0.29E–10	0.0	0.0	0.0	0.0
40000– 50000	0.0	0.0	0.0	0.0	0.0
50000– 75000	0.0	0.0	0.0	0.0	0.0
75000–100000	0.0	0.0	0.0	0.0	0.0

Differential Neutron Spectra

(still considerable uncertainties!)



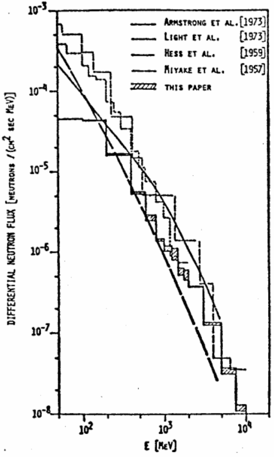
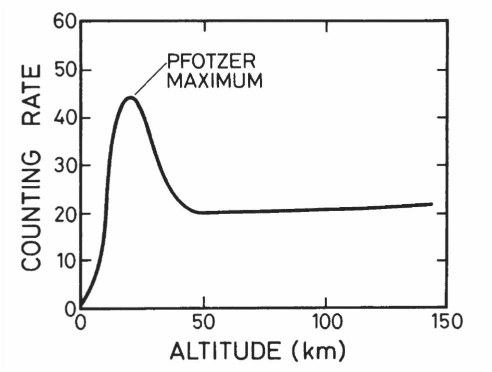


Figure 1. Differential neutron flux at atmospheric depth $h = 650\ \text{g cm}^{-2}$.

Hagmann et al., 2007

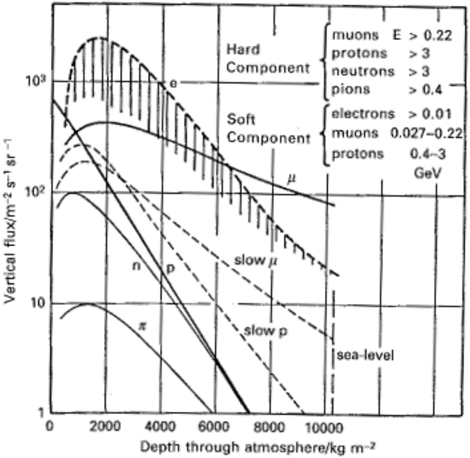
Vertical Development I



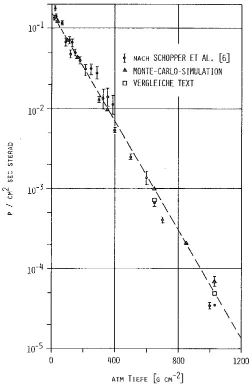
The production of secondary components becomes significant at ∼55 km and reaching a maximum (Pfotzer maximum) at ∼20 km.

Vertical Development II

Different species of secondary cosmic rays in the atmosphere



Attenuation of Protons in the Atmosphere



Attenuation of vertical intensity > 1 GeV proton

Altitude dependence of hadron flux, I:

$$I(0^\circ, X_2) = I(0^\circ, X_1)\exp\left(-\frac{X_2 - X_1}{\lambda}\right)$$

where $X_2 \geq X_1$, λ is the attenuation length

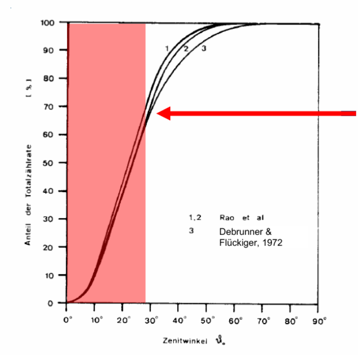
Attenuation length for CR-induced secondary protons (and neutrons):

$\lambda_{GCR} \sim 130$ g cm^{-2}

$\lambda_{SCR} \sim 100$ g cm^{-2}

$\Rightarrow$ attenuation length defines barometric coefficient of neutron monitors!

Dependence on primary zenith angle



This explains why we can use „vertical cutoff rigidities“ in many applications!

Dependence of the contribution to the total neutron monitor count rate on the zenith angle of the primary cosmic radiation at the top of the atmosphere

Ion Production in the Earth's Atmosphere

Electromagnetic radiation from the Sun and inciendent galactic and solar cosmic rays (GCR and SCR) are ionising the Earth's atmosphere.

The energy flux of GCR falling on the Earth's atmosphere is about 10^8 times smaller in comparison with solar electromagnetic irradiation

But: at altitudes $h \sim 3$ to 35 km, cosmic rays are the main ionising contributor

Ion production and ion concentration in the Earth's atmosphere

Ion production rate, q:

$$q = I \cdot \frac{\rho \cdot \sigma}{M}$$

where

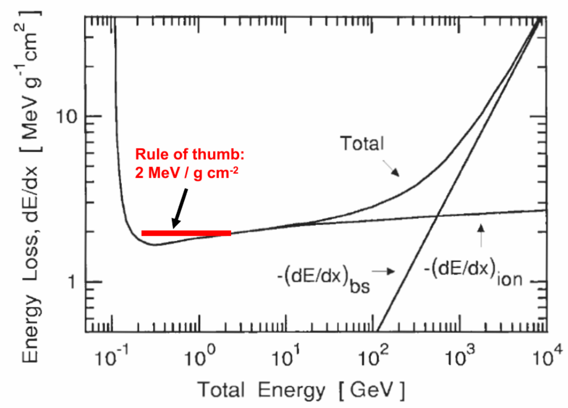
$I = I(h, R_c, > Phi)$	cosmic ray flux at altitude h
ρ	air density
σ	effective ionisation cross section $\approx 2 \cdot 10^{-18}$ cm^2 at $h \leq 20$ km
M	average mass of air atom

Ion concentration, n:

$$q = \alpha \cdot n^2$$

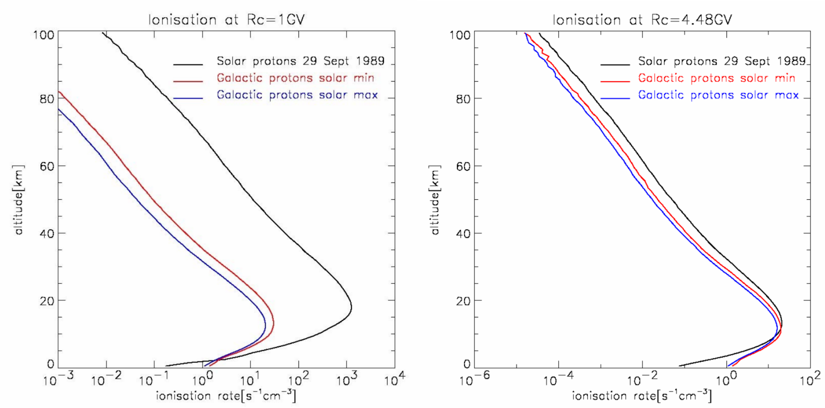
where α is the recombination coefficient

Ionisation



Energy loss of muons by electromagnetic interactions versus its total energy.

Ionisation in the atmosphere by SCR



Desorgher et al., AOGS 2004

Take home message I

- 1 GeV = J
- 1 GV proton = MeV
- typical B_{IMF} = nT
- B_{Earth} = Gauss
- K_p-index?

- Cutoff rigidity at geomagnetic aeuquator?
- Cutoff rigidity at high latitudes?

Take home message I

- 1 GeV = $1.6 \cdot 10^{-10}$ J
- 1 GV proton = MeV
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Take home message I

- 1 GeV = $1.6 \cdot 10^{-10}$ J
- 1 GV proton = $\sim$450 MeV
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Take home message I

- 1 GeV = $1.6 \cdot 10^{-10}$ J
- 1 GV proton = ∼450 MeV
- typical B_{IMF} = 5 nT
- B_{Earth} = Gauss
- K_p-index?

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Take home message I

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- 1 GV proton = $\sim$450 MeV
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Take home message I

- 1 GeV = $1.6 \cdot 10^{-10}$ J
- 1 GV proton = ∼450 MeV
- typical B_{IMF} = 5 nT
- B_{Earth} = 0.3-0.6 Gauss
- K_p-index?

- Cutoff rigidity at geomagnetic aeuquator?
- Cutoff rigidity at high latitudes?

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- K_p-index? K_p-index quantifies the disturbance of the Earth's magnetic field with an integer in the range 0-9 with 0 being calm and 5 or more indicating a geomagnetic storm.
- Cutoff rigidity at geomagnetic aeuquator?
- Cutoff rigidity at high latitudes?

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Take home message I

- 1 GeV = $1.6 \cdot 10^{-10}$ J
- 1 GV proton = ~450 MeV
- typical B_{IMF} = 5 nT
- B_{Earth} = 0.3-0.6 Gauss
- K_p-index? K_p-index quantifies the disturbance of the Earth's magnetic field with an integer in the range 0-9 with 0 being calm and 5 or more indicating a geomagnetic storm.
- Cutoff rigidity at geomagnetic aeuquator? ~15 GV
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Take home message I

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- Cutoff rigidity at geomagnetic aeuquator? ~15 GV
- Cutoff rigidity at high latitudes? ~0 GV, i.e. below atmospheric cutoff

Take home message II

- The three components of secondary cosmic rays in the atmosphere?
- Most abundant component of secondary cosmic rays?
- Most abundant component at ground?
- Mean life times of pions and muons?
- Pfotzer maximum? At which altitude?
- Typical energy loss of charged particles by electromagnetic interactions?

Take home message II

- The three components of secondary cosmic rays in the atmosphere? Electron or soft component, hadron component, muon component
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- Pfotzer maximum? At which altitude? Local intensity maximum of secondary cosmic ray flux in the atmosphere at an altitude of $\sim$20 km
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- Typical energy loss of charged particles by electromagnetic interactions? 2 MeV / (g cm^{-2})