Cosmic rays and space weather: direct and indirect relations

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http://space.saske.sk

(Space Weather, J.Freeman,1995)

Conditions on the Sun, in solar wind, magnetosphere, ionosphere and thermosphere, which can influence reliability of space and technological systems and can endanger health of people.

Energetic particles in space (including CR) may cause SEU (single event upsets), radiation damage, degradation of materials, charging of elements of cosmic systems. At higher energies, especially CR van influence the electronics on airplanes.

Effects: hf radio systems. Geomagnetic storms can influence ground technological systems, pipelines, telecommunication cables, railway systems due to induced currents.

Radiation (including CR) is a limiting factor for interplanetary missions.

CR vs SW: direct and indirect relations

A. EFFECTS OF COSMIC ENERGETIC PARTICLES ON MATERIALS.

1. Interaction of high energy particles with matter [1] .

High energy particles interacting with materials contribute to 3 types of processes:

ionisation or excitation of atoms/molecules

destruction of crystal structures and molecular chains

nuclear interactions (at very high energy).

Depending on the type of interaction between beam-particle and target, the scattering process is called ***elastic, inelastic or deeply inelastic***. In an *elastic scattering* process the *incident and target particles are left intact* and only their momenta may be changed. In an *inelastic scattering* process the *target particle is excited*. For example if a nucleus is bombarded by neutrons, it may be excited to some nuclear resonance. In *deep inelastic scattering* the *target* (and sometimes the incident particle) *is destroyed* and completely new particles may be created.

1.1. Energy losses of heavy particles.

1.1.1. Ionisation losses.

important for ***detector design***; for production of ***secondary particles in atmosphere***

Incident heavy particles (p, heavier nuclei) are passing ***without significant deviation in material*** (straight line).

Simplified assumptions: charged particle (z.e, M, p=M.v, M>>m_e) crossing material with minimum distance of closest approach to electron (b - collision parameter; e, m_e charge and mass of electron) transfers to electron the kinetic energy:

$$p^2/2.m_e = (z^2.e^4)/(8.\pi^2.\varepsilon_o^2.b^2.v^2.m_e) \qquad (1)$$

Maximum kinetic energy lost in one interaction is $E_{max} = 2.m_e.v^2$

The elementary loss of energy is *averaged (integrated) over* realistic *range of b* (b_{max} estimated from the assumption that duration of interaction is < period of electron on its orbit; b_{min} either from classical physics – closest approach corresponding to b at which electrostatic potential energy of interaction is equal the maximum energy transfer ($2.m_e.v^2$) or from quantum mechanics – uncertainty principle $\Delta x.\Delta p > \hbar/2$; choice according to smaller of the two estimates of b_{min})

and *averaged per unit length.*

For non-relativistic case the energy loss per unit length x is

$$-dE/dx = (z^2.e^4.N_e/4.\pi.\varepsilon_o^2.v^2.m_e).\ln(2.m_e.v^2/I) \qquad (2)$$

where N_e is number of electrons per unit volume ($N_e=N_{atom}.Z$, I is the ionisation potential of material (estimate of $I=16 . Z^{0.9}$ (eV), Z – atomic number of medium). Including relativistic losses ***Bethe-Bloch formula*** is : $-dE/dx = (z^2.e^4.N_e/4.\pi.\varepsilon_o^2.v^2.m_e).[\ln(2.\gamma^2.m_e.v^2/I) – \beta^2]$ (3)

where $\gamma = (1 - \beta^2)/^{-1/2}$; $\beta=v/c$.

Usually instead of x (length) the ***thickness is measured in g.cm^{-2} or kg.m^{-2}*** (total mass per unit cross-section which particle is passing through).

Detailed Bethe-Bloch formula assuming other effects (screening corrections of inner electrons, density corrections because of polarisation of medium). It can be found e.g. at

http://pdg.lbl.gov/2005/reviews

(2005 web update of Review of Particle Physics)

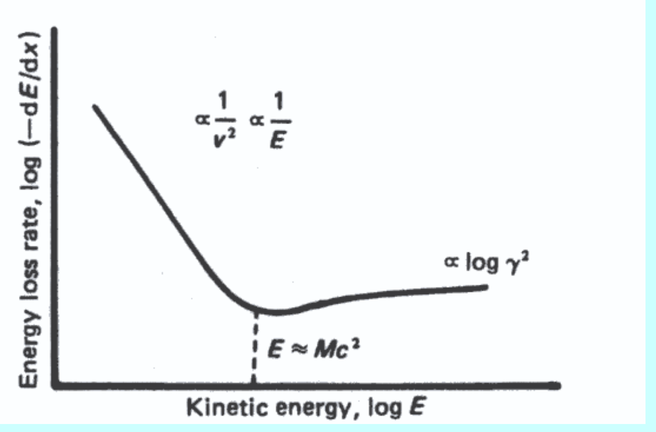
In section Passage of particles through matter (Rev.)

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right] \qquad (4)$$

In units MeV.g^{-1}.cm^2, where T_{max} is maximum kinetic energy which can be imparted to a free electron in a single collision, K = A . 0.307 MeV.g^{-1}.cm^2, A is in g.mol^{-1}, δ is density effect correction for ionisation loss.

*Citation: S. Eidelman et al., Phys. Lett. B **592**, 1 (2004)*

Ionisation energy loss is independent of mass M of particle; it varies as approximately $\sim 1/v^2$ at non-relativistic velocities, it increases logarithmically beyond minimum at $E_{kin} \sim M.c^2$; depends relatively weakly on medium (Z/A is not strongly different from 0.5).



From [1]

dE/dx is often called *stopping power* of material and expressed usually in form of $dE/d\xi$ (ξ in $MeV/g.cm^2$ or $MeV/kg.m^2$) .

$\xi = \rho \,.\, x$ (5) (ρ is density of material)

$-dE/d\xi = z^2 \,.\, f(v) \,.\, Z/m$ (m is mass of nucleus of material). (6)

Since Z/A is rather insensitive to Z, the form (6) is useful, because the only change of energy loss rate for different elements is the ionisation potential I.

From [1]

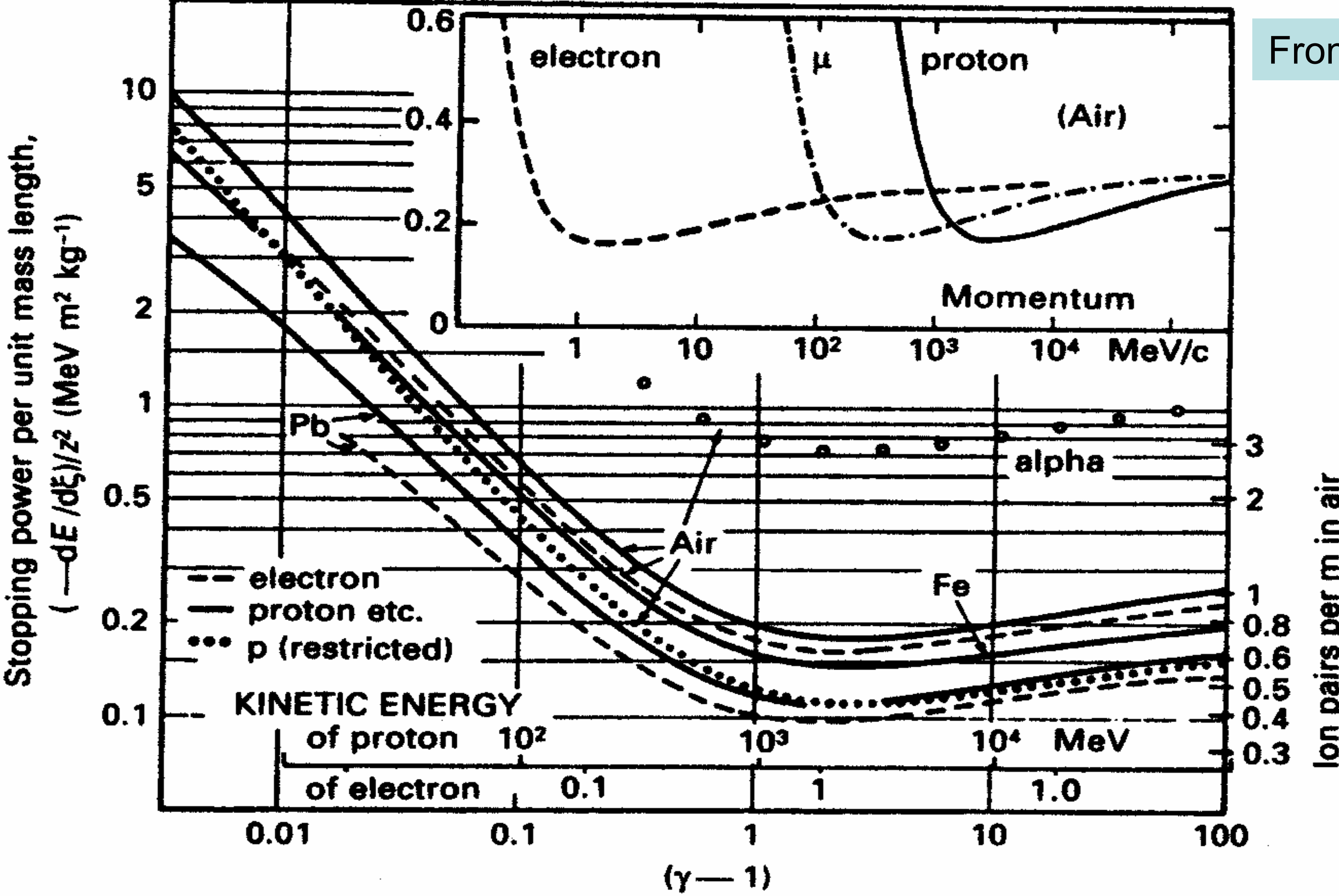
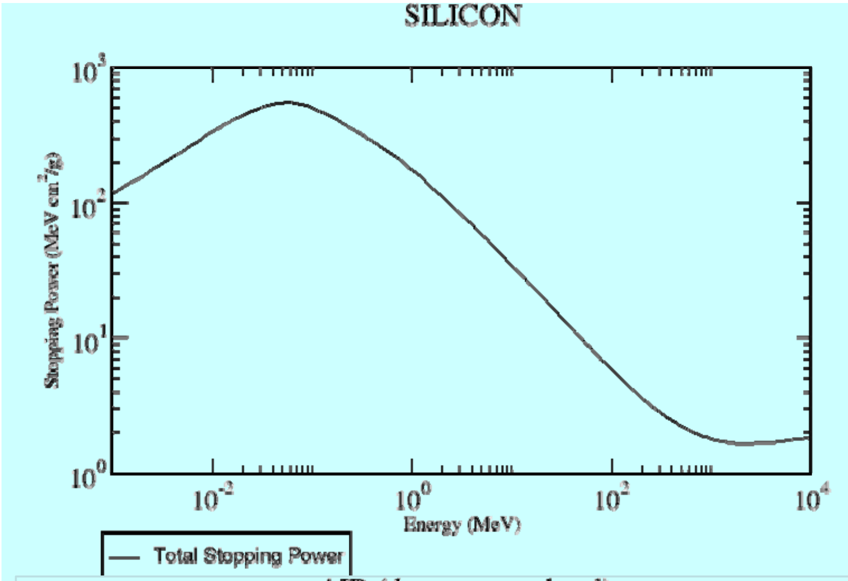
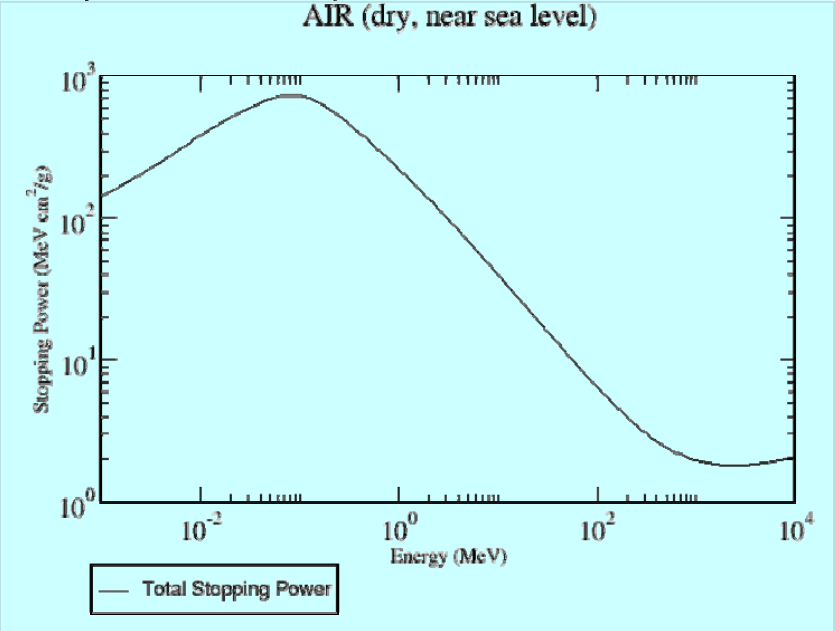


Figure 2.7. The energy loss rate due to ionisation losses in various materials. In contrast to Fig. 2.6, these curves extend into the relativistic regime, $\gamma \gg 1$. The diagram shows both the values of the Lorentz factor γ and the kinetic energies of the particles. The inset shows the loss rates in air as a function of the momentum of the particles. (From A. M. Hillas (1972). *Cosmic rays*, page 30, Oxford: Pergamon Press.)

Useful are tables and graphs available at
http://physics.nist.gov/PhysRefData/Star/Text/programs.html
Two examples of stopping power of protons (in Si and in air).





Initial energy of particle (E_0) can be estimated (if only ionisation losses are dominant) from distance to which it travels. The distance to the rest is called *range*. Ionisation is most intensive at the end of the track of particle. The *range R* is defined

$$R = \int_{E0}^{0} dx = - \int_{0}^{E0} dE/(dE/dx) = \int_{0}^{E0} dE/(z^2.f(v).Z/m) \qquad (7)$$

Using (6) and $E = (\gamma-1).Mc^2$; $dE = d(\gamma Mc^2) = Mv.\gamma^3.dv$

$$Rz^2/M = (m/Z) . \int_{0}^{E0} (v.\gamma^3/f(v))\, dv \qquad (8)$$

Value (8) is only *function of initial velocity* or kinetic energy per nucleon.

Range gives information about kinetic energy/nucl of particle, its charge z and mass M.

Normalized range (expressed as Rz^2/M (8)) is rather insensitive to material into which is particle injected.

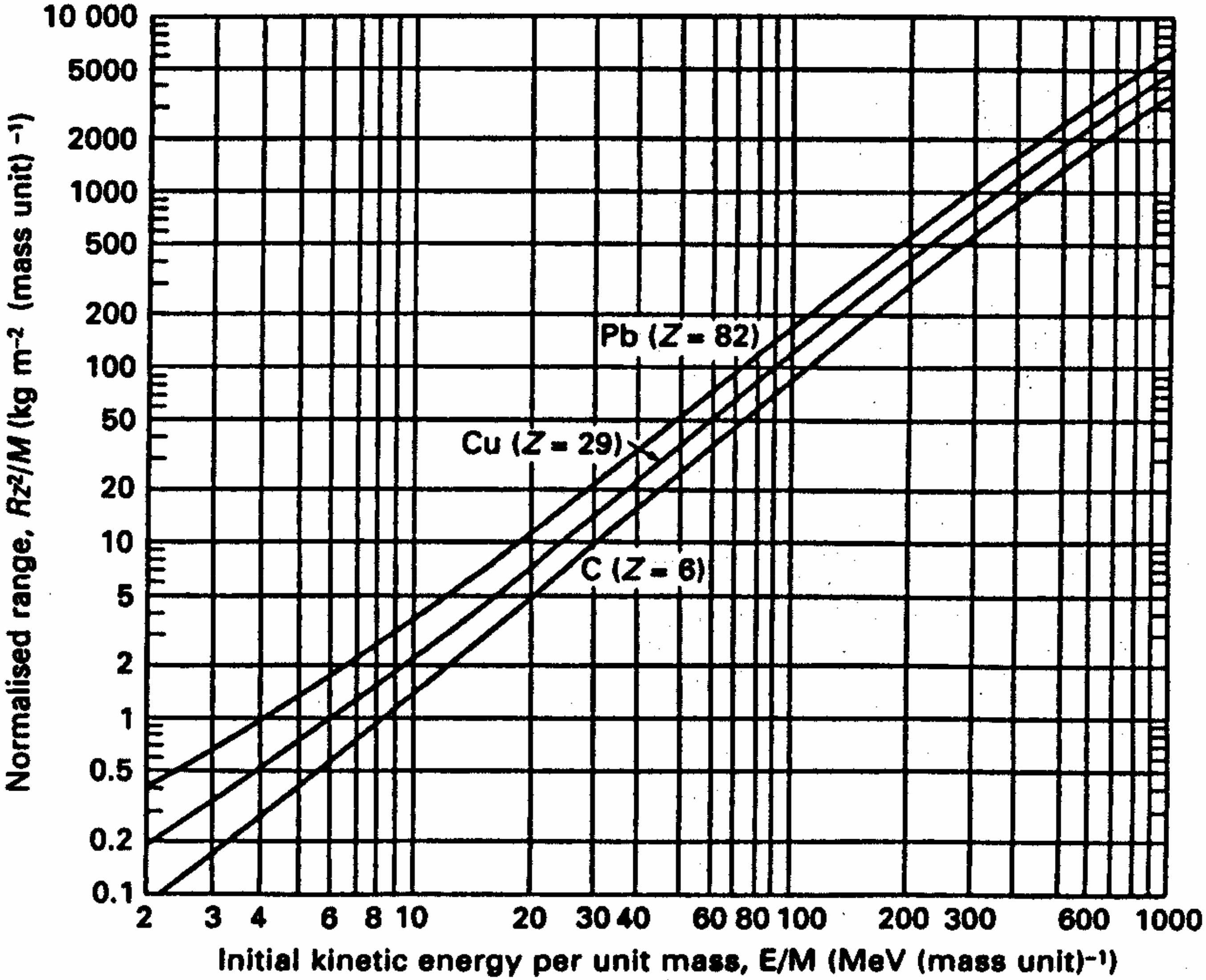


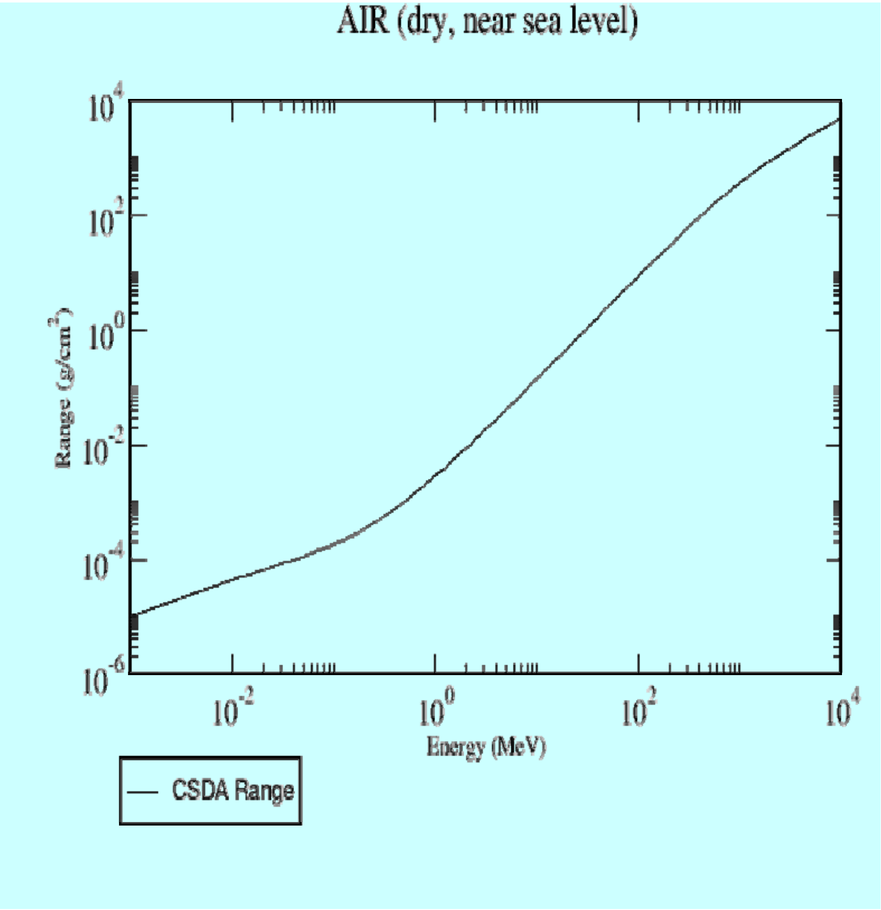
Figure 2.8. The ranges for protons in carbon, copper and lead measured in terms of their path lengths in kg m^{-2}. The scales are such that the graph may be scaled for particles other than protons. (From H. A. Enge (1966). *Introduction to nuclear physics*, page 186, London: Addison-Wesley.)

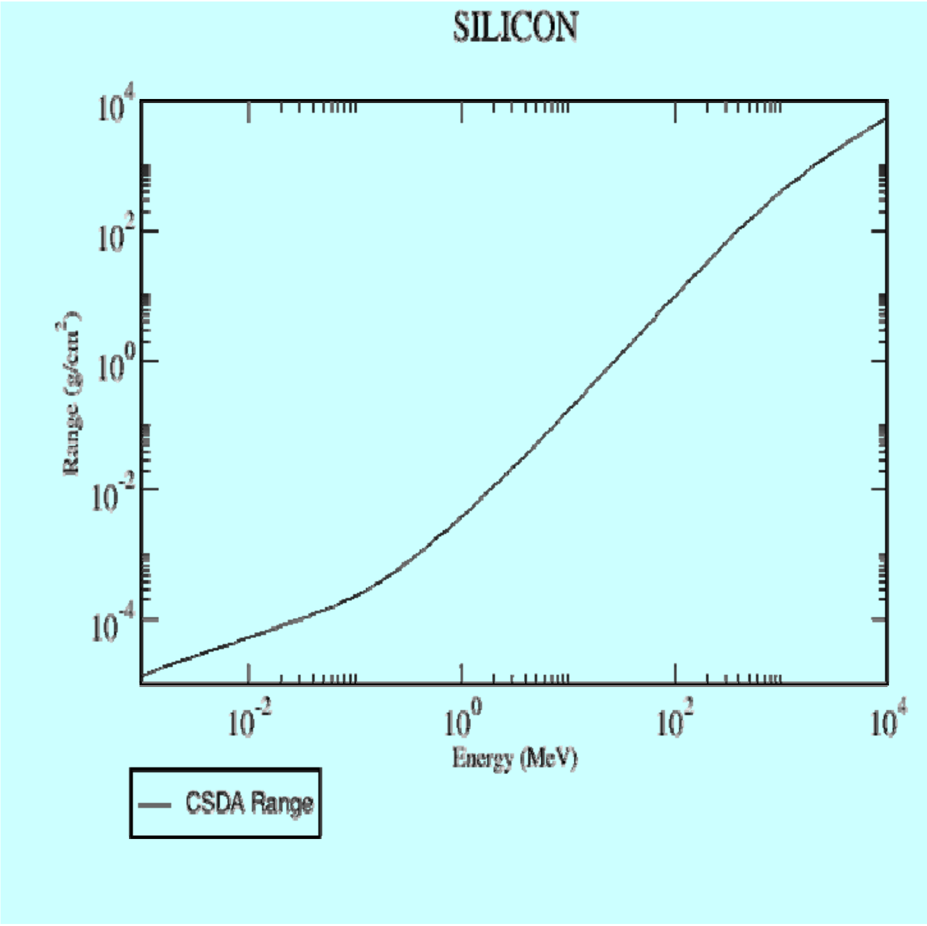
From [1]

Ranges for protons and alpha particles can be found at

http://physics.nist.gov/PhysRefData/Star/Text/programs.html

Examples for air and Si, protons (continuous slowing-down approximation).





Example.

Using a simplified barometric formula for atmosphere (e-folding altitude in density 7.4 km, total depth 1030 g.cm^{-2}) estimate the altitude at which 10 MeV and 100 MeV proton entering the top of atmosphere from interplanetary space deposits maximum energy for ionisation (in polar regions).

1.1.2. Nuclear interactions.

Simplified approach. Strong interaction forces are *short-range forces*. The cross-section of nuclear interactions can be assumed geometrically (geometric cross-section of nucleus). Nucleus radius in very simplified form is approximated as $R = 1.2 \,.\, 10^{-15} \,.\, A^{1/3}$ (m). Cosmic rays (primary) have typical energy > 1 GeV. Further simplification: de Broglie wave of particles has $\lambda << $ distance between nucleons in nuclei (e.g. 10 GeV proton has $\Delta x \sim \hbar/\gamma . m_p . c = 0.02 \,. 10^{-15}$ (m), much smaller than R).

Thus *incident proton* (also heavier nucleus) *is assumed as a discrete and small particle interacting with individual nucleons in nucleus*.

Number of particles with which it interacts is just number of nucleons along the line of sight through nucleus.

If proton passes through O or N nucleus, it interacts with approximately $15^{1/3}$ (~2.5) nucleons. The incident proton undergoes multiple scattering inside nucleus.

Cosmic ray proton interactions. Empirical picture:

- p interacts with an individual nucleon in nucleus, and *principal products of the collision are* π^o, π^-, π^+.
- In CMS (center mass system) frame of p-nucleon encounter, *pions are moving mainly in forward and backward direction*
- *Nucleons and pions* all posess high forward motion in laboratory frame and they *come out of the interaction with high energy*
- Each of *secondary particles* is capable of *initiating another collision in the same nucleus*, *if the initial collision* occurred close to the *front edge of nucleus* (minicascade is initiated inside nucleus).
- *Only 1-2 nucleons participate in interaction with high energy particle*, but they are removed from the *nucleus* leaving it *in highly excited state* – various processes may occur: often several *nuclear fragments* (spallation fragments) *evaporate from nucleus* mostly isotropically in laboratory frame. *Neutrons* are also evaporated.

- *Mean free path* of high energy *proton (for nuclear interaction*) in the atmosphere is ~ 80 $g.cm^{-2}$ (800 $kg.m^{-2}$), much less than the total depth of the atmosphere (1030 $g.cm^{-2}$).

- *Proton flux* of given energy *falls more slowly* (p survives the interaction with some energy loss). For particles of a given energy, the number density of protons falls as $\exp(-\xi/L)$, L=120 $g.cm^{-2}$.

- Empirical rule: *protons > 1GeV*, in collision with air nuclei, generate ~ *2.* $E^{1/4}$ *new, high energy, charged particles* (E in GeV) mostly pions. Pions of all charges are produced in almost same number except low energies (π^+ favours in this case).

Cosmic ray nuclei interactions.

(heavier CR nuclei with N, O in atmosphere). *Sometimes*, several pairs of nucleons undergo pion-producing collisions and usually *the target nucleus is "destroyed". More common* are grazing encounters (only few nucleons interact to produce a shower of pions) and *residual nuclei are left in exciting state*.

High energy fragments can develop into separate showers, and at very high energies *(>10^{17} eV) some of showers penetrate the surface of Earth*.

1.2. Energy losses of electrons.

Ionisation losses. The main difference in ionisation losses of heavy particles and electrons: (a) *interacting particles have the same mass* (electrons) – maximum energy transferred is different

$E_{max} = \gamma^2.m_e.v^2/(1+\gamma)$, and (b) electrons *are scattered* (deviated) from their original direction *substantially*.

Formula for ionisation losses of electrons [1] is

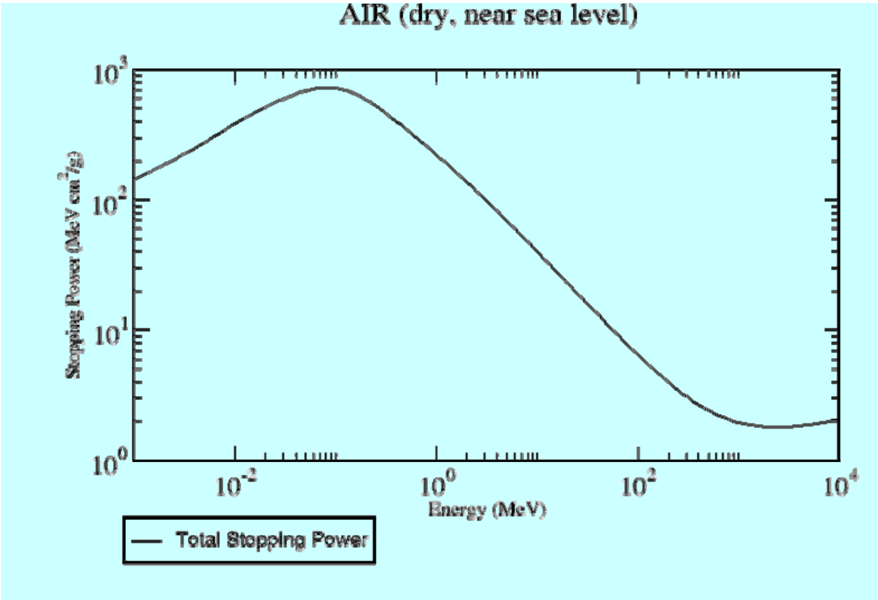
$$-dE/dx = e^4.N.Z/(8\pi.\varepsilon_o{}^2.v^2) \,.\, [\ln(\gamma^2.m_e.v^2.E_{max})/(2.I^2)) -$$

$$-(2/\gamma - 1/\gamma^2)\ln 2 + 1/\gamma^2 + 1/8.(1-1/\gamma)^2)] \qquad (9)$$

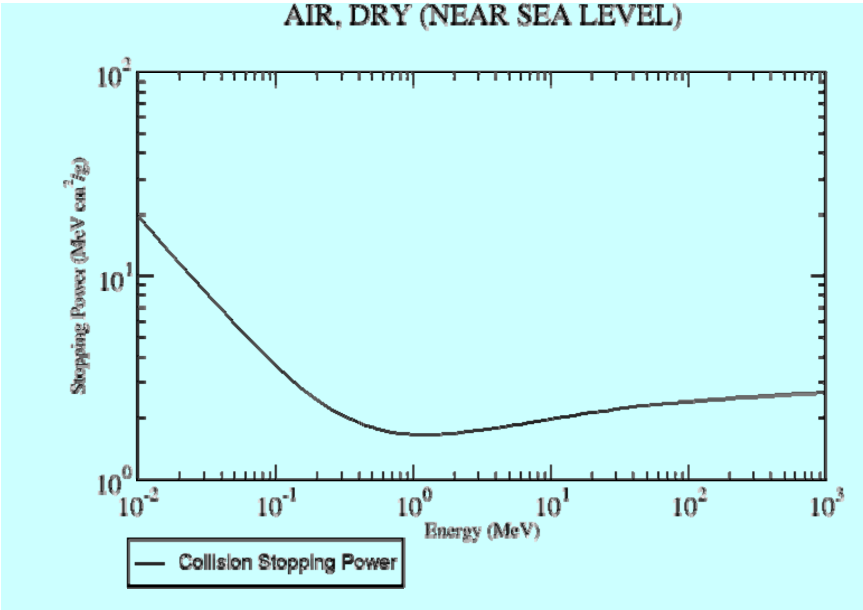
The –dE/dx dependence on E is similar to that of protons, but ***at the same kinetic energy the loss rate of proton energy is higher than that of electron.***

Energy loss rate of protons and electrons for ionisation (comparison):

(From http://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html and ESTAR.html)



p



e

Significant difference of electron energy loss with that of proton is ***bremsstrahlung*** *(breaking radiation).*

If a ***charged particle is accelerated or decelerated, it emits electromagnetic radiation*** (in the encounter between electron and nuclei of the material). At high energy, for electrons this process is more important than ionisation.

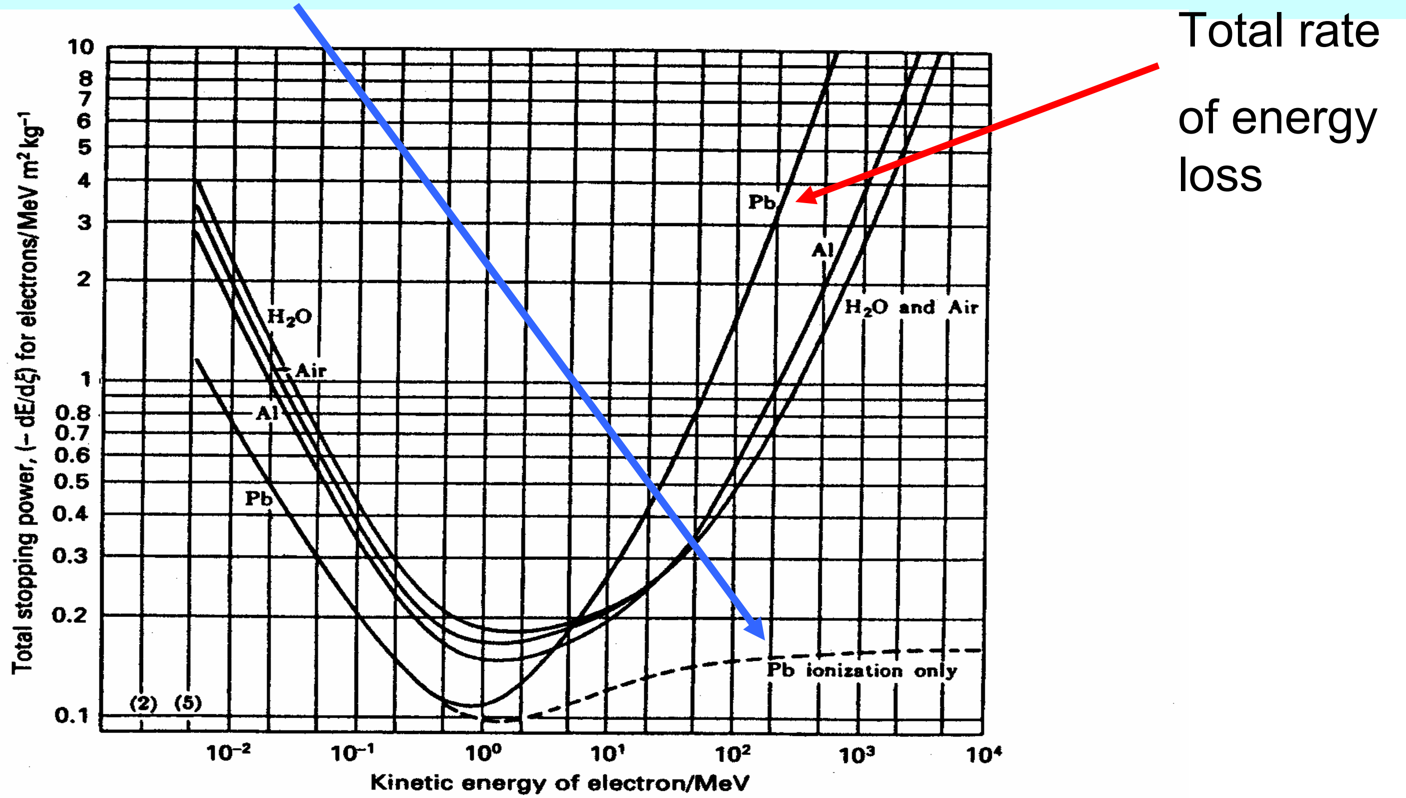
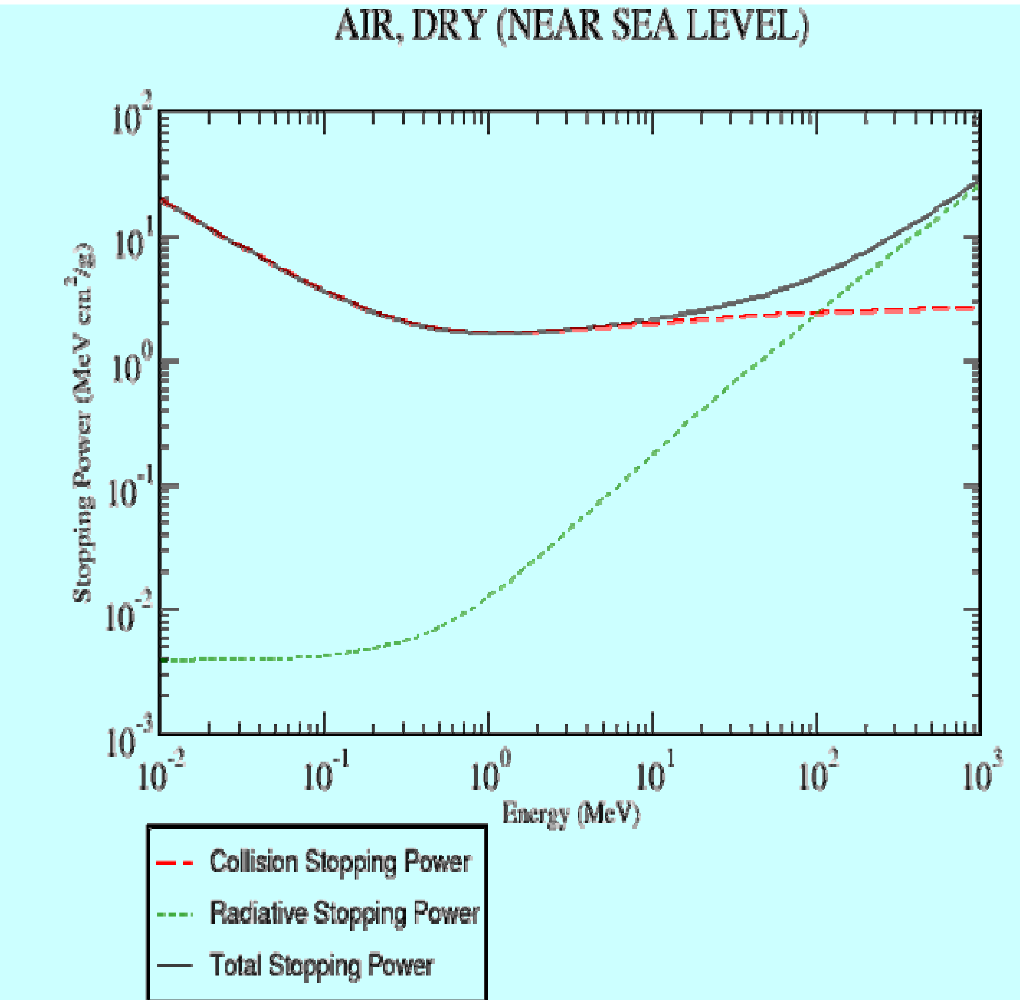


Figure 3.5. The total stopping power for electrons in air, water, aluminium and lead. At energies less than 1 MeV, the dominant loss mechanism is ionisation losses. At higher energies, the dominant loss process is bremsstrahlung. For comparison, the contribution from ionisation losses for electrons in lead is also shown. (From H. A. Enge (1966). *Introduction to nuclear physics*, page 190, London: Addison-Wesley Publishing Co.)

For relativistic energies Bethe - Heitler formula gives rate (change in time) of radiation loss by electron:

$$-dE/dt = (Z.(Z+1.3).e^6.N/(8\pi^2.\varepsilon_o^3.m_e^2.c^4.h)) .E.[\ln(183/Z^{1/3})+1/8] \qquad (10)$$

(From http://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html)



Relativistic radiation losses of energy have exponential form

($-dE/dx \sim E$).

In ultra-relativistic limit

$-dE/d\xi = E/\xi_o$

$\xi_o = \rho.x_o$ - radiation length

ρ is density of target

$$1/\xi_o = \frac{4\alpha N_A Z(Z+1)\, r_e^2 \log(183\, Z^{-1/3})}{A}$$

$$\begin{aligned}
\alpha &= \text{fine structure constant} (\approx 1/137) \\
N_A &= \text{Avogadro's number } (6.022 \cdot 10^{23}/\text{mole}) \\
Z &= \text{atomic number of the traversed material} \\
A &= \text{atomic weight of the traversed material} \\
r_e &= \text{electron radius } (2.818 \cdot 10^{-13}\ \text{cm}).
\end{aligned}$$

From: http://rd11.web.cern.ch/RD11/rkb/PH14pp/node153.html

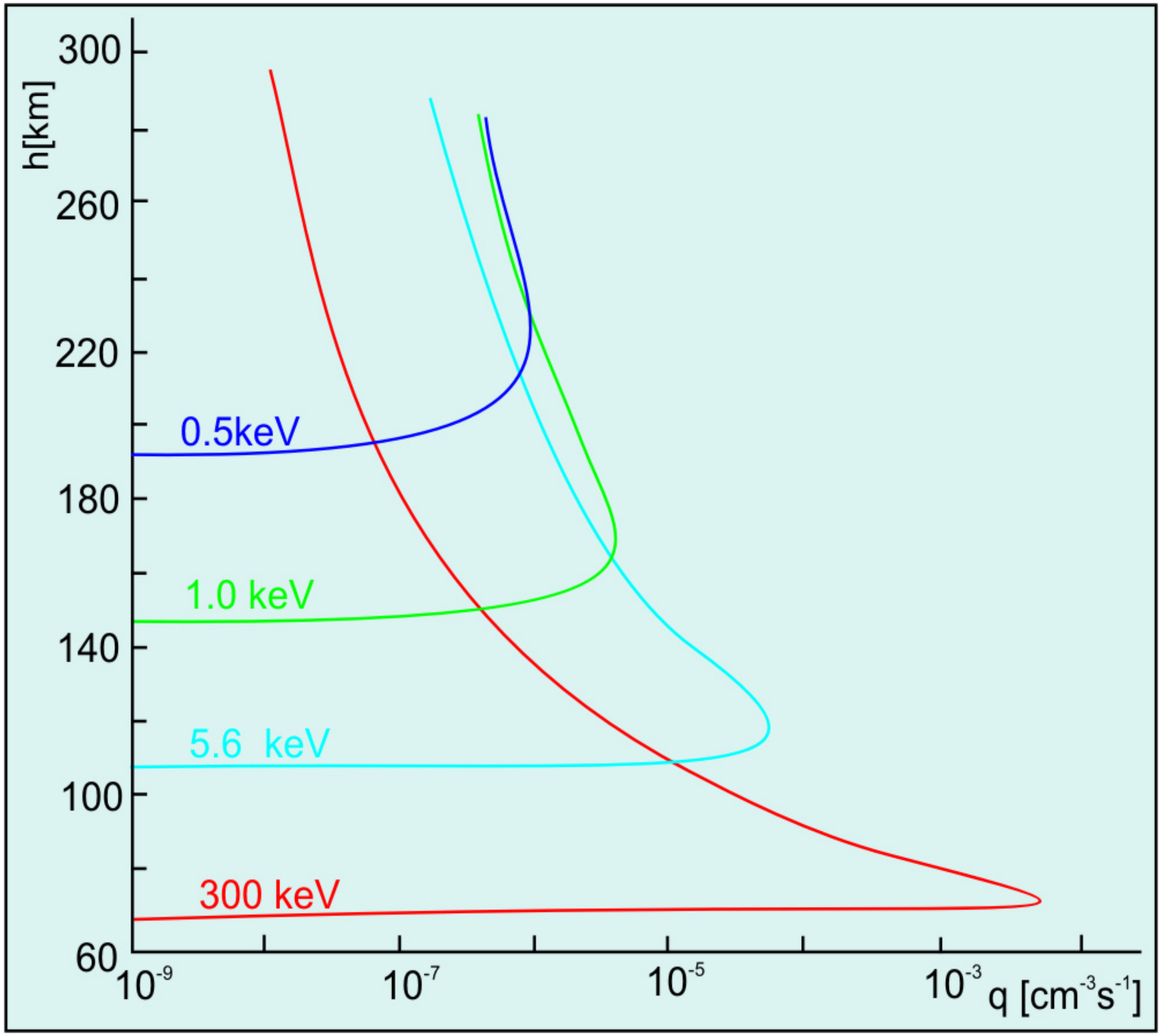
ξ_o is in g.cm^{-2}. For air ξ_o = 580 kg.m^{-2} (= 580 m at sea level), much lower than total depth of atmosphere (~ 10300 kg.m^{-2}).

Critical energy (*at which bremsstrahlung losses are equal to ionisation losses*), is approximately:

$$E_c = \frac{610\,\mathrm{MeV}}{Z + 1.24} \quad , \qquad\qquad E_c = \frac{710\,\mathrm{MeV}}{Z + 0.92} \quad .$$

for liquids, solid state — for gases

Penetration of electrons into the atmosphere.
Production rate of ions is on x axis.



According to *(M.H. Rees, Planet. Space Sci., 11, 1209, 1963)*, the altitude profiles of the rate of ion production in the atmosphere along the 1cm of the electron path has a maximum close to the range of electrons and below that it is abruptly decreasing. The profiles have energy as a parameter. For 300 keV the peak is about 70 km, for 40 keV about 95 km, for 6 keV about 110 km.

1.3. Energy losses of energetic photons.

3 processes are important in different energy ranges: photoelectric effect, Compton scattering, pair production (e^-e^+). At very high energies also nuclear reactions .

Exponential loss of energy with length (depth). Data on absorption coefficients available e.g. for energy 1 keV – 20 MeV in various materials at http://physics.nist.gov/PhysRefData/XrayMassCoef/cover.html

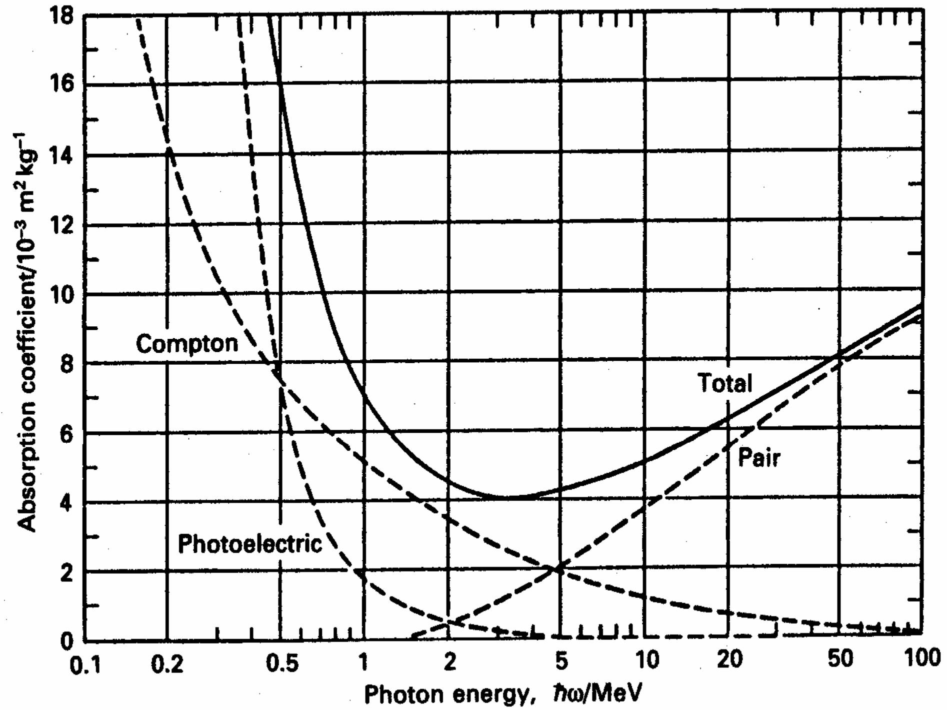
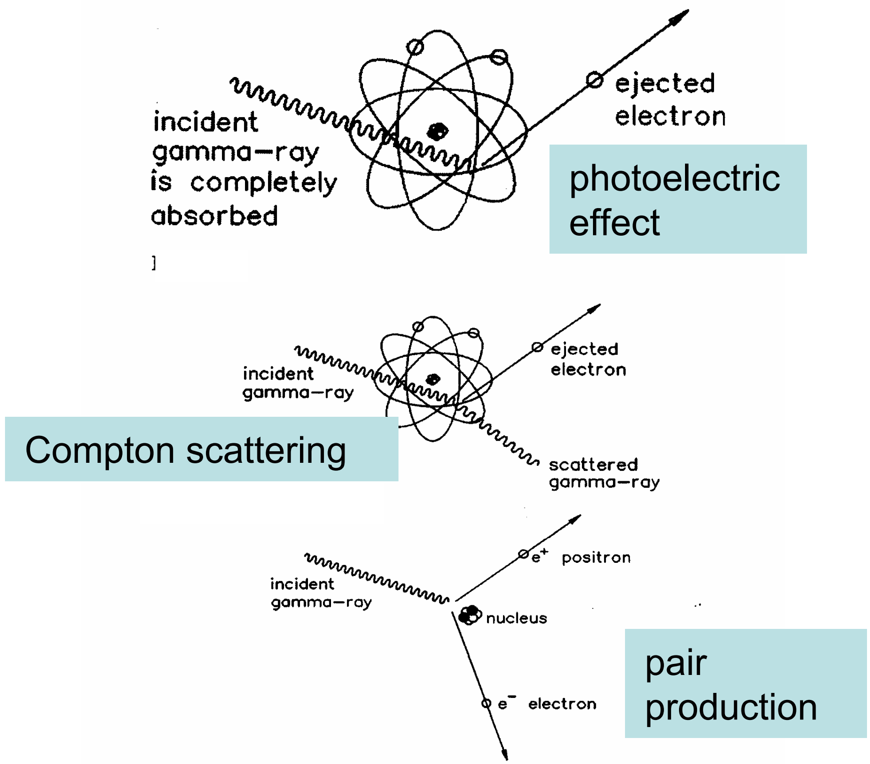
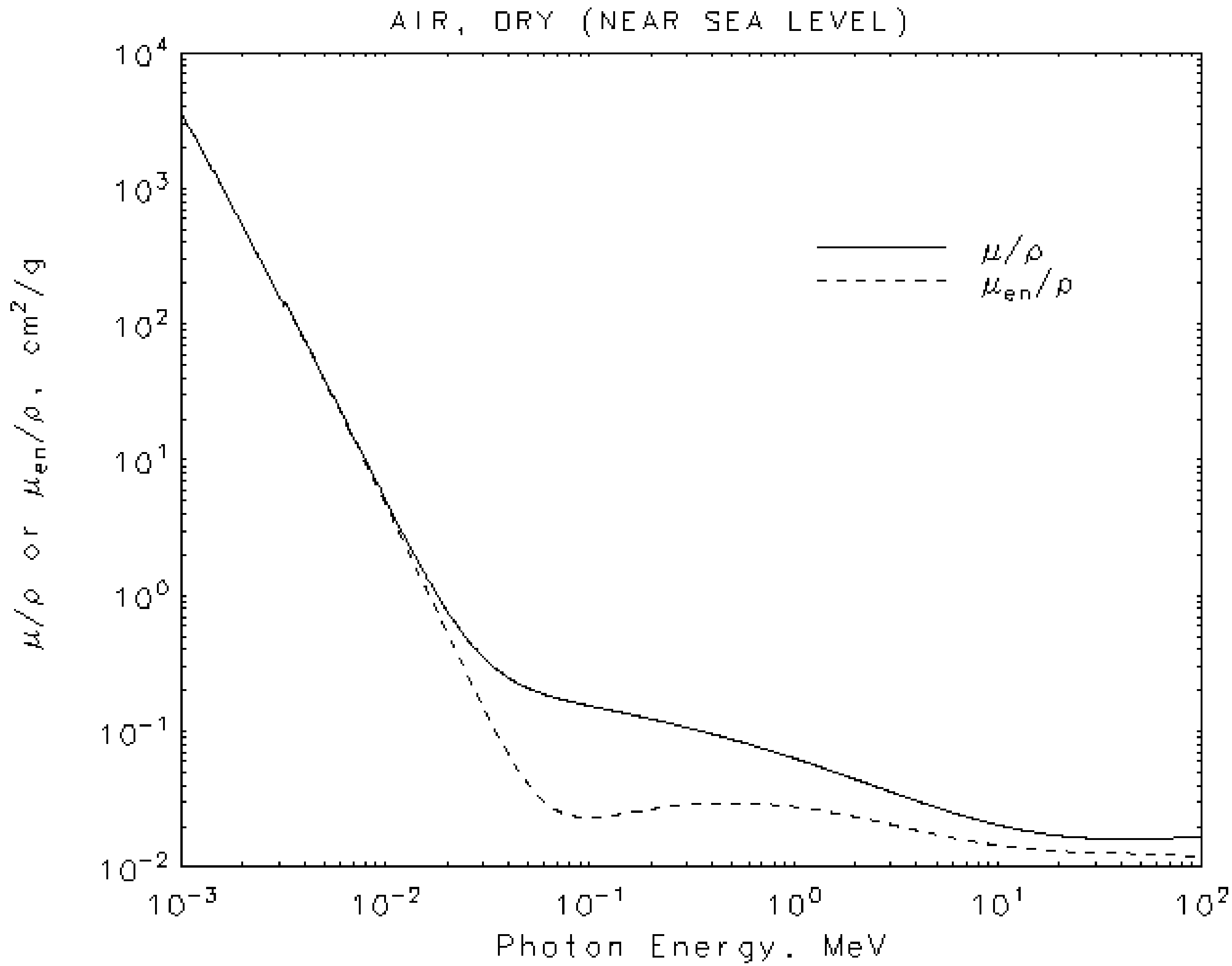


Figure 4.16. The total mass absorption coefficient for high energy photons in lead, indicating the contributions associated with the photoelectric absorption, Compton scattering and electron–positron pair production. (From H. A. Enge (1966). *Introduction to nuclear physics*, page 193, London: Addison-Wesley Publishing Co.)





A narrow beam of monoenergetic photons with an incident intensity I_o, penetrating a layer of material with mass thickness x and density ρ , emerges with intensity I given by the exponential attenuation law **$I = I_o \cdot \exp((-\mu/\rho).x)$,** μ/ρ – mass attenuation coefficient. (http://physics.nist.gov/PhysRefData/XrayMassCoef/).

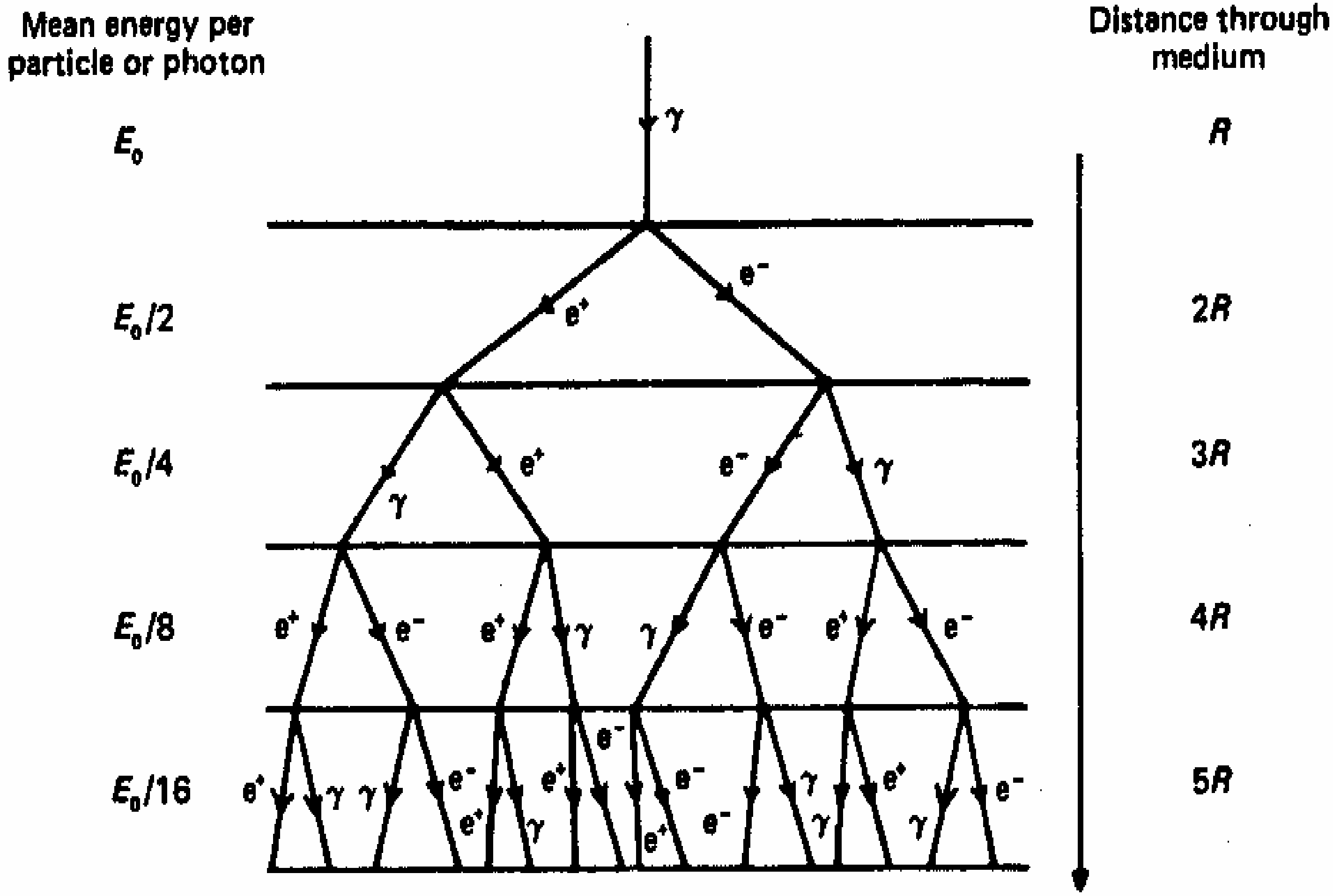
Electron-photon cascades (electromagnetic showers)

High energy photon ($E > 2.m_e.c^2$) *generates* (in the presence of another body – nucleus) the *pair of e^- and e^+.* The *radiation length of pair production* is the same as that of *bremsstrahlung of ultra-relativistic electrons.*

e^-e^+ (at high E) generate high energy photons by bremsstrahlung; each of photons generate (if sufficient E) pair e^-e^+ etc. Probability of these processes taking place at distance ξ is 0.5

$$\exp(-\xi/\xi_o) = 1/2 \; ; \; \xi = R = \xi_o.\ln 2$$

The cascade is initiated. γ of energy E_o, after a distance of (average) R, produces e^+e^- pair (e^+ and e^- share the energy $E_o/2$). In next distance R, due to bremsstrahlung e^+ and e^- lose their energy and create photons with $E_o/4$ energy.



Simple model of electromagnetic cascade (from [1]). After distance n.R, the number of (e^+,e^- and photons) is 2^n, each with average energy $E_o/2^n$ (2/3 e^+ and e^-, 1/3 photons).

Below E_c the cascade begins to slow down (other losses are dominant at larger distance).

The shower reaches its ***maximum*** when average energy of particles in cascade is **~ E_c**. Number of (photons, e^+,e^-) is ≈ E_o/E_c and distance (in radiation lengths N) is $N = \ln(E_o/E_c)$.

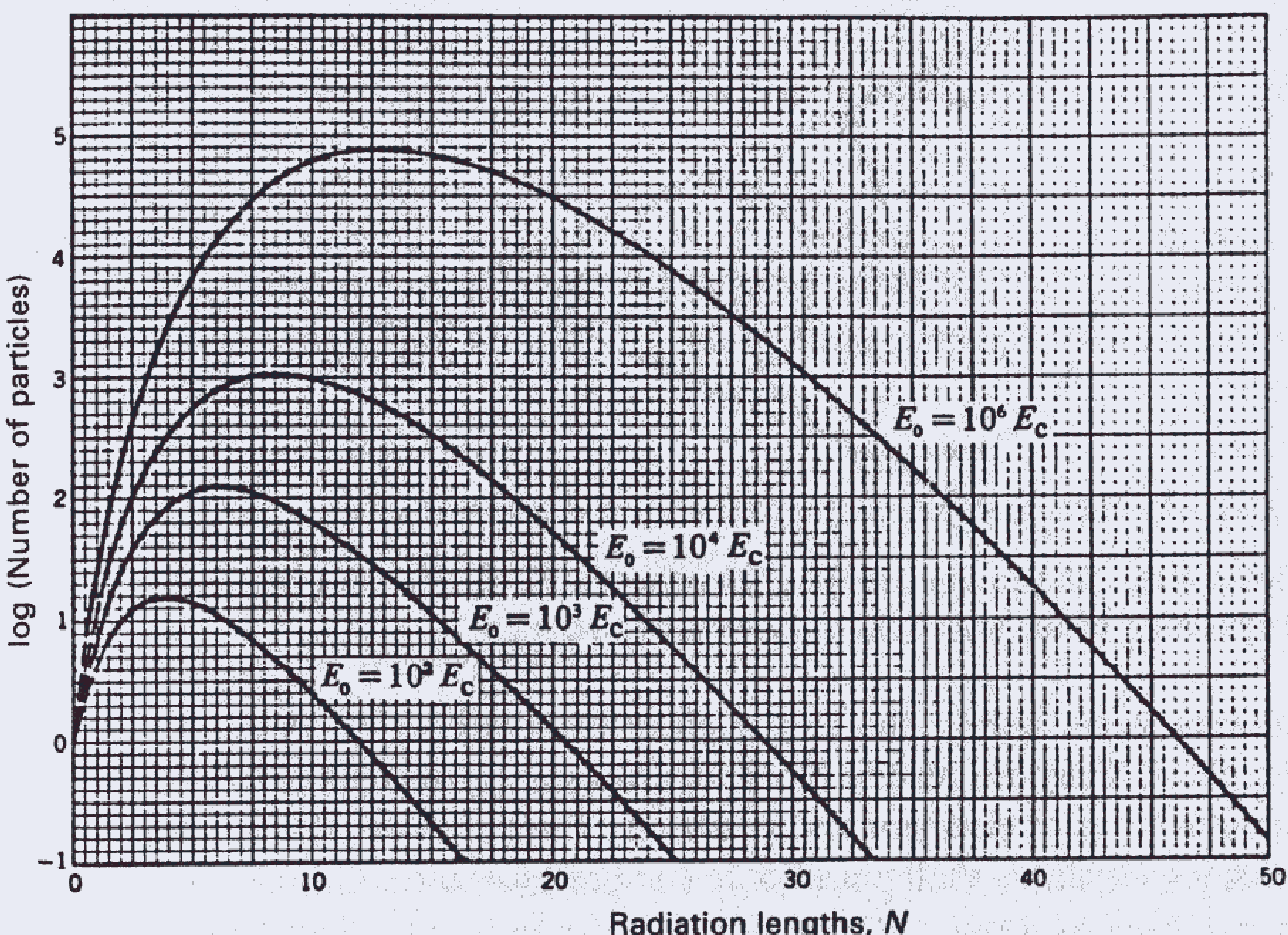


Figure 4.18. The total number of particles in a shower initiated by an electron of energy E_0 as a function of depth through the medium measured in radiation lengths N; E_c is the critical energy. (From B. Rossi and K. Greisen (1941). *Rev. Mod. Phys.*, **13**, 240.)

2. Cosmic rays in the atmosphere.

„History“ of secondary cosmic rays.

1. Secondary nucleons and charged pions are produced (“pionisation”, if energy is sufficient for pion production) continue in initiation of nuclear interactions until their energy is < 1 GeV. Nucleon cascade.

2. Secondary protons lose their energy for ionisation and most of them at < 1 GeV is consequently stopped.

3. Neutral pions (π^o ,short lifetime ~1.8 . 10 $^{-16}$ s) are decaying into 2 gammas. These initialize electromagnetic shower. Charged pions (lifetime ~ 2.55 . 10^{-8} s) are during their passage through atmosphere decaying into muons

$$\pi^+ \rightarrow \mu^+ + \overline{\nu_\mu}$$

$$\pi^- \rightarrow \mu^- + \nu_\mu$$

Muons *do not initiate nuclear reactions* and are slowed down via ionisation losses. Low energy muons “succeed” to decay (their lifetime ~ 2.20 . 10^{-6} s)

$$\mu^+ \rightarrow e^+ + \overline{\nu_e} + \nu_\mu$$

$$\mu^- \rightarrow e^- + \nu_e + \nu_\mu$$

Muons produce e^+,e^-. However, most of them have high energy at high altitude in atmosphere, low ionisation losses, and they penetrate deep into low atmosphere.

In their own frame of reference they decay with τ=2.2 μs. In laboratory system (e.g. measurements on earth surface) the lifetime is

$$\tau_{lab} = \tau \, . \, \gamma \qquad (11)$$

(Lorentz factor γ). Muons with sufficiently large γ come to the surface not decayed. First evidence on relativistic dilation of time and on contraction of lengths.

HE μ may penetrate below earth surface – underground measurements (high energy cosmic rays, detection of cosmic ray arrival directions, directional telescopes).

Interactions depend only on total thickness of material (atmosphere, detector). If detectors at earth surface measure the total ionisation of secondary particles, the energy of the primary cosmic ray particle can be deduced.

Example: To what characteristic distance in atmosphere penetrates π^o of total energy 2 GeV (created in nuclear interaction by primary CR proton). Compare it with distance to which charged muon (μ^+ or μ^-) of the same total energy penetrates. The rest masses of π^o and of μ^- are 0.135 and 0.1056 GeV/c^2 respectively.

From http://www.ngdc.noaa.gov/stp/SOLAR/COSMIC_RAYS/image/shower.gif and *A.M. Hillas, Cosmic rays, 1972*.

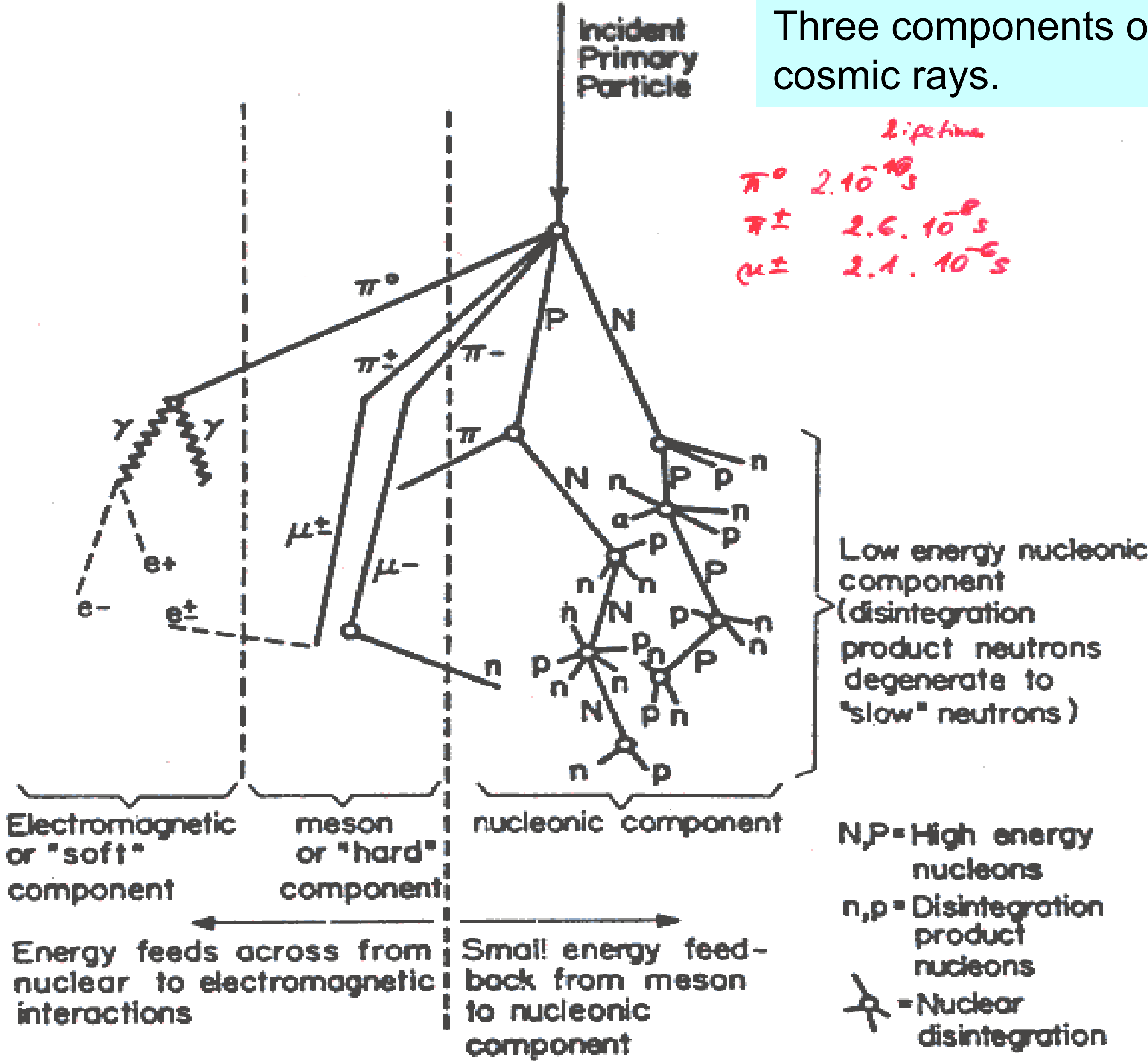
Three components of secondary cosmic rays.

Lifetime

π^0 2.10^{-16} s

$\pi^\pm$ $2.6.10^{-8}$ s

$\mu^\pm$ $2.1.10^{-6}$ s



Flux of secondary cosmic rays in atmosphere. From *A.M. Hillas, 1972*.

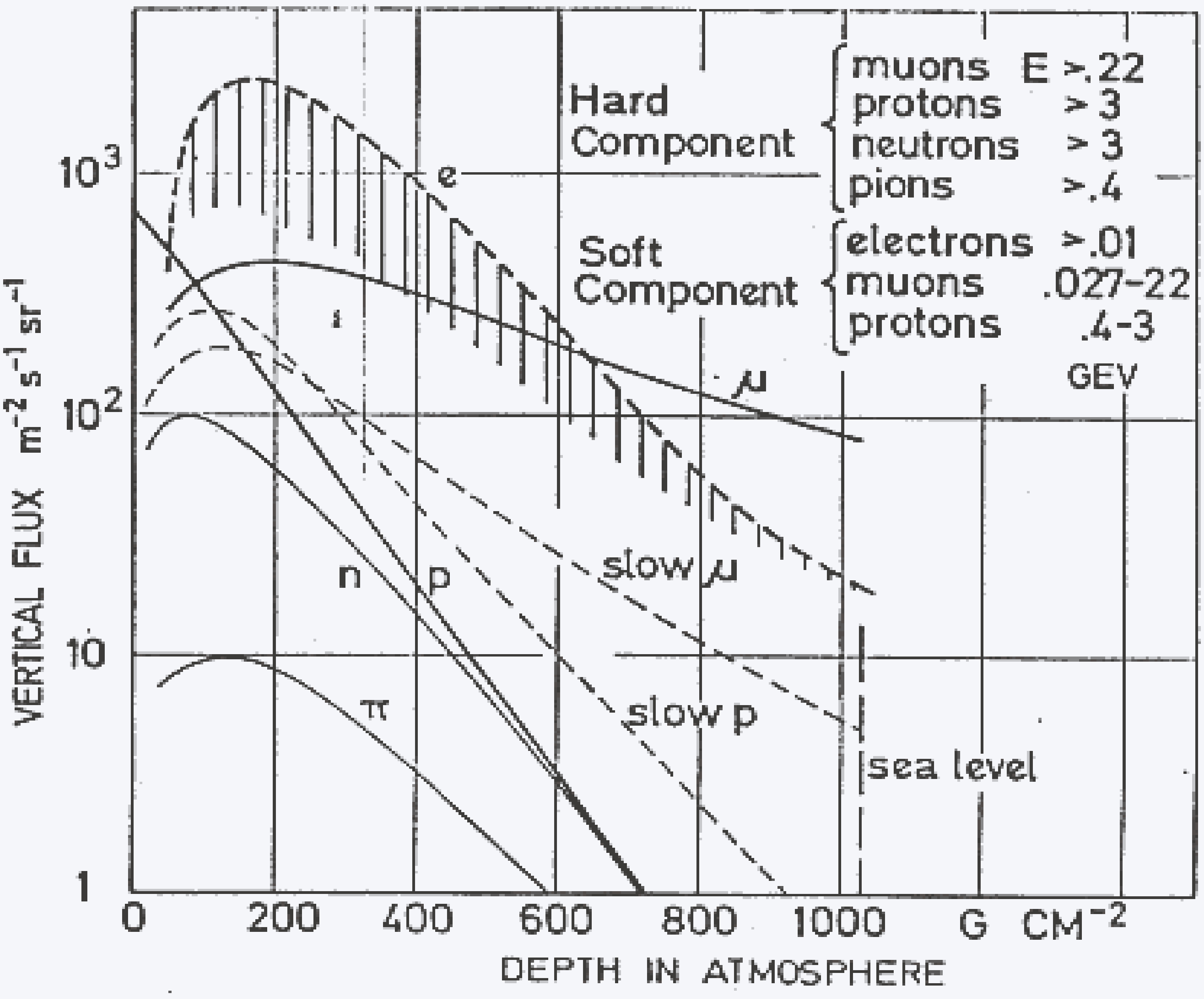
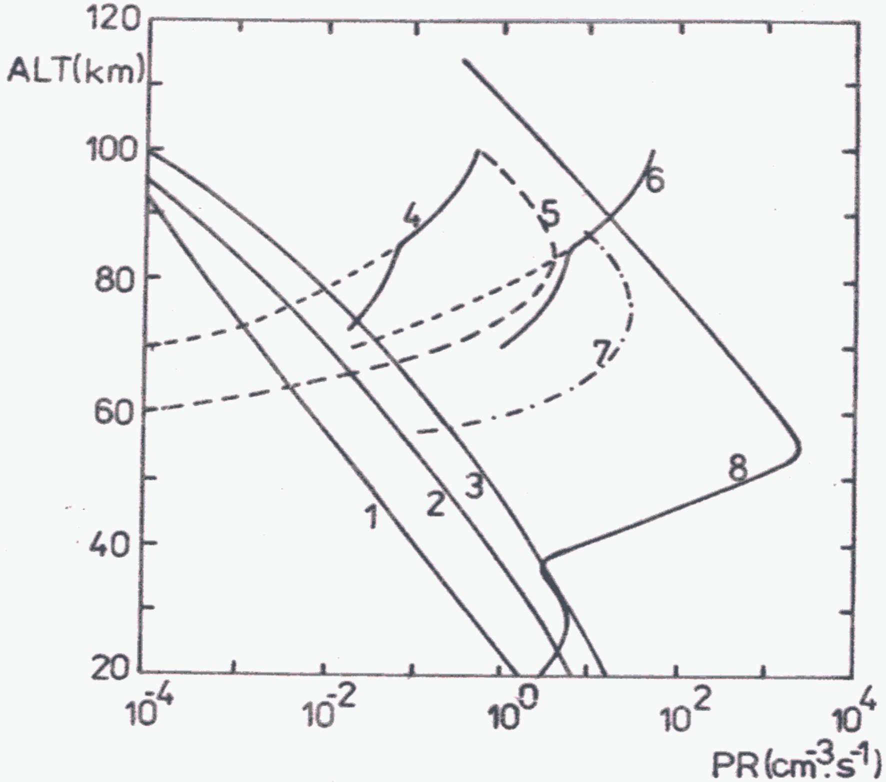


FIG. 12. Components of the radiation in the atmosphere, after Peters.



Ionisation (production rate of ions) in atmosphere at different altitudes by cosmic rays and by other energetic particles. Simplified picture.

Compilation of :
Vampola and Gorney, 1983
Baker et al, 1987
Sheldon et al, 1988

1, 2, 3 - GCR at 0°, 70° s.max, 70° ~~s.min~~

Velinov, 1974

4, 6 - solar H_α (scattered, direct)

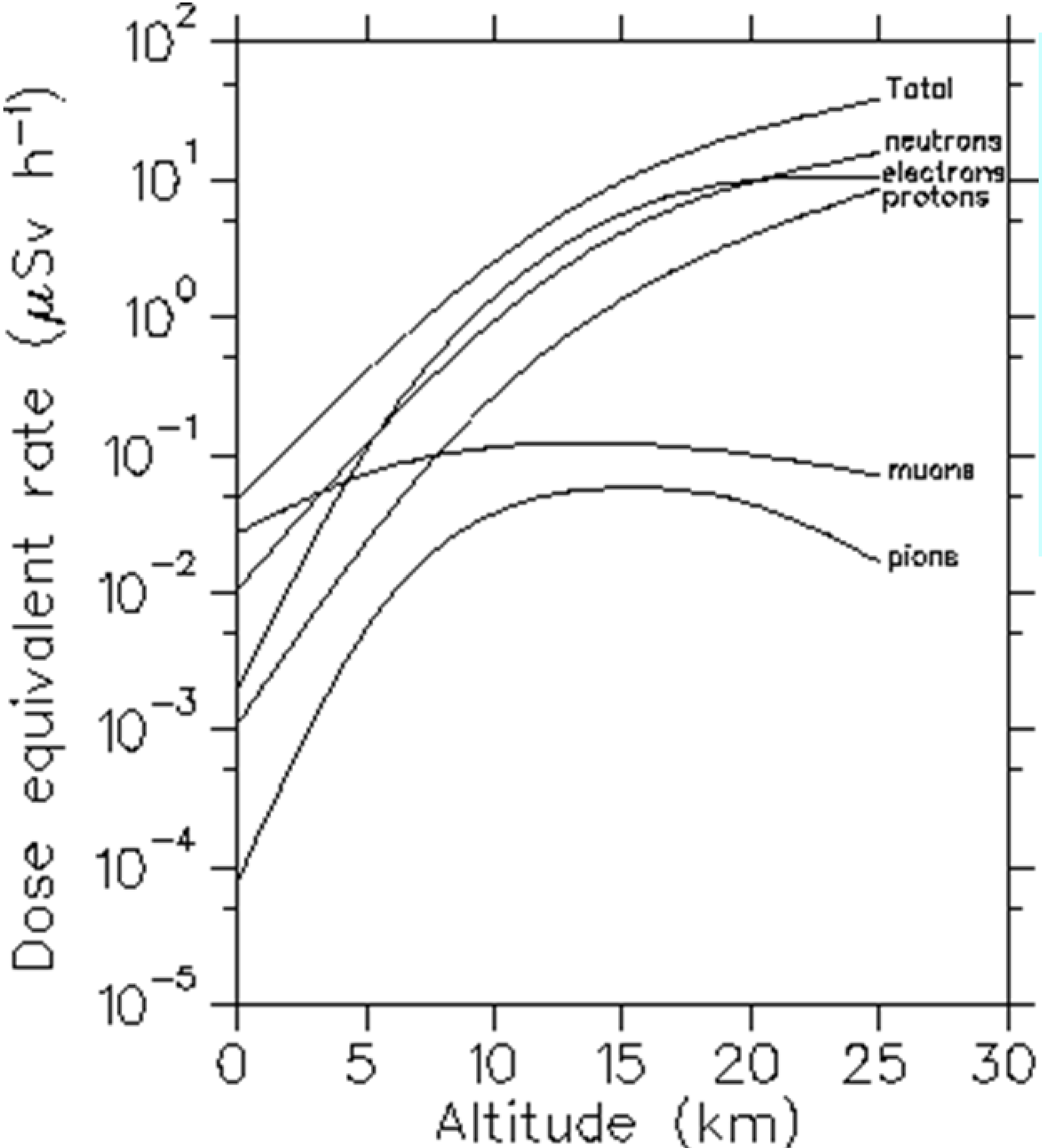
5, 7 - due to e precipitation (quiet, $K_p = 6_-$) at $L=4$

8 - due to relativistic electrons (assumed $L \in (3, 8)$)

3. *Exposure to natural radiation and to cosmic rays.*

Man's Exposure To Ionizing Radiation, from http://www.arpansa.gov.au/is_rad.htm

Source Of Exposure	**Exposure**
Natural Radiation (Terrestrial and Airborne)	1.2 mSv per year
Natural Radiation (**Cosmic radiation at sea level)**	**0.3 mSv per year**
Total Natural Radiation	**1.5 mSv per year**
Seven Hour Aeroplane Flight	0.05 mSv
Chest X-Ray	0.04 mSv
Nuclear Fallout (From atmospheric tests in 50's & 60's)	0.02 mSv per Year
Chernobyl (People living in Control Zones near Chernobyl)	10 mSv per year
Cosmic Radiation Exposure of Domestic Airline Pilot	2 mSv per year



Contribution to the dose by ***galactic*** cosmic rays at different altitudes at 55°N geomagnetic latitude.

From (*Reitz, G., Rad. Protect. Dosim., 48, 65-72, 1993*).

Values of dose equivalent rates from http://sel.noaa.gov/info/RadHaz.html
Galactic Cosmic Rays only

Dose Equivalent Rate (micro-sieverts per hour (μSv/h))

	Solar Minimum (10/86)		**Solar Maximum (7/89)**	
Altitude (x1000 ft)	35 degrees North Latitude	70 degrees North Latitude	35 degrees North Latitude	70 degrees North Latitude
0	0.0401	0.0412	0.0374	0.0380
10	0.190	0.207	0.173	0.181
20	0.985	1.14	0.875	0.953
30	3.25	4.06	2.85	3.24
40	6.78	9.02	5.88	6.99
50	9.71	13.8	8.36	10.3
60	11.1	17.1	9.49	12.3
70	11.4	19.2	9.68	13.3
80	11.2	20.6	9.44	13.8

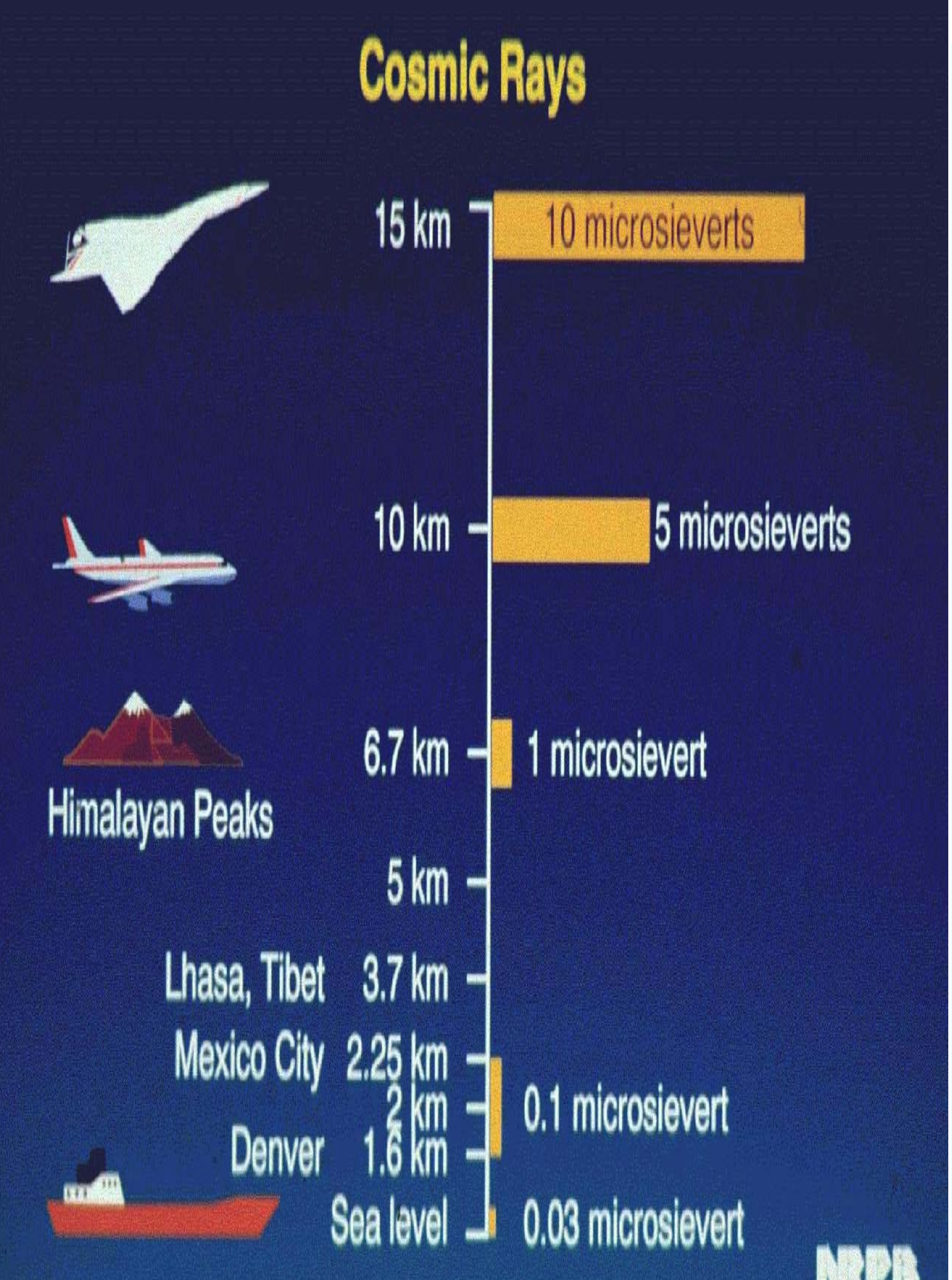
COSMIC RAY IMPLICATIONS FOR HUMAN HEALTH

TABLE I

Variation in cosmic ray exposure

Effect	Range of variation	Within Magnetosphere
Altitude	Factor of 1000	From sea level to 80 000 ft
Latitude	Factor of ~2	Highest at polar latitudes
Solar cycle	Factor of ~2	Highest at high latitude
Solar protons	Variable	Highest at polar latitudes; short lived transient events

From (*Shea, M.A. and Smart, D.F., Space Sci. Rev., 93, 187-205, 2000*).



Bartlett,2001

Solar CR significantly change the situation.

For 1 week of stay at **10km**, 1GV is dose 0.7 mSv (from GCR)

During strong flare 23.2.1956 twice (only hours)

During „weaker“ flare in 1989 it is already half during 2-3 hours

At 17 km: total dose from GCR ~1.8mSv

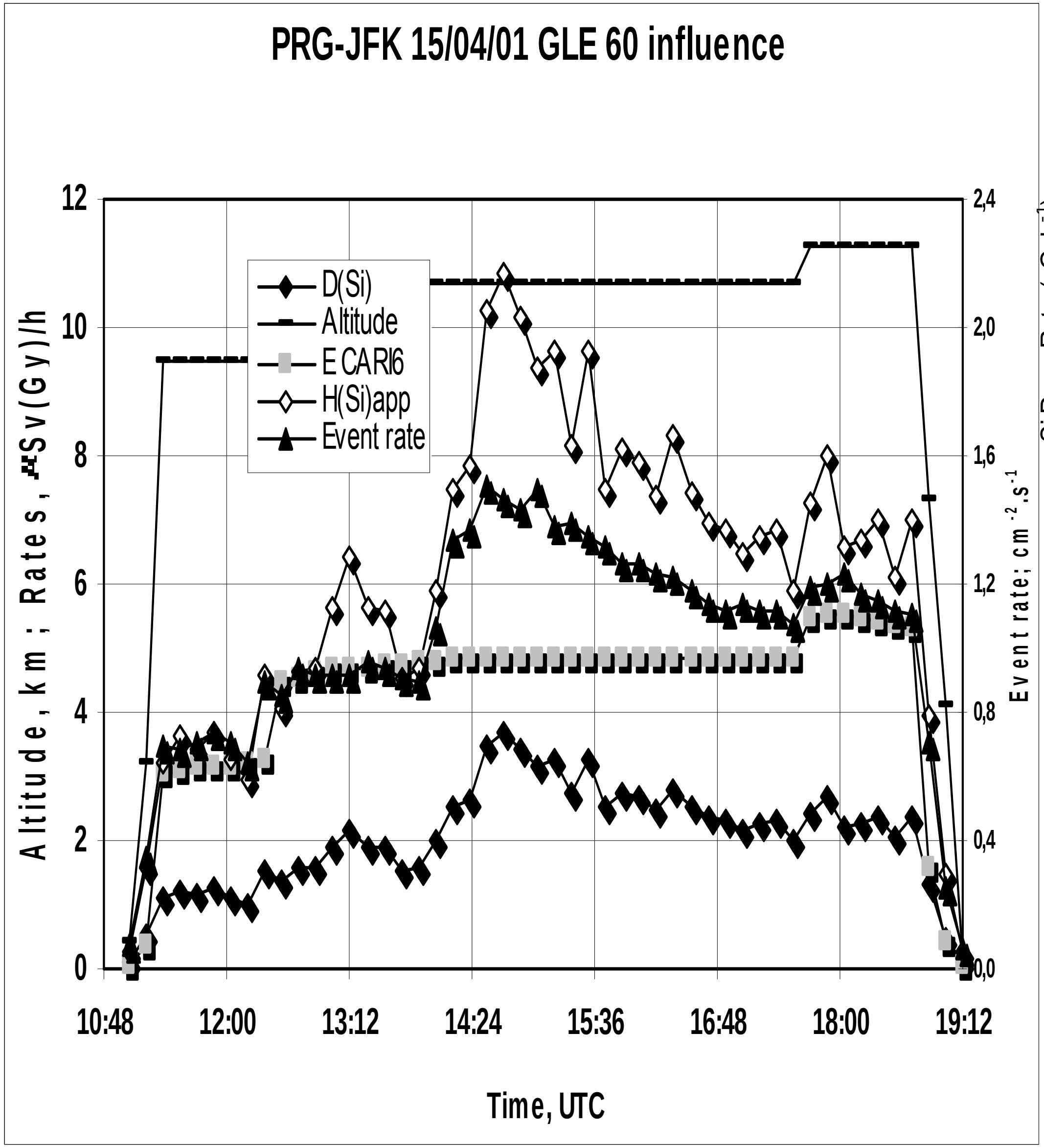
During extreme solar flare in 1956 it should be 9.3mSv (1SEU each 7 s!)

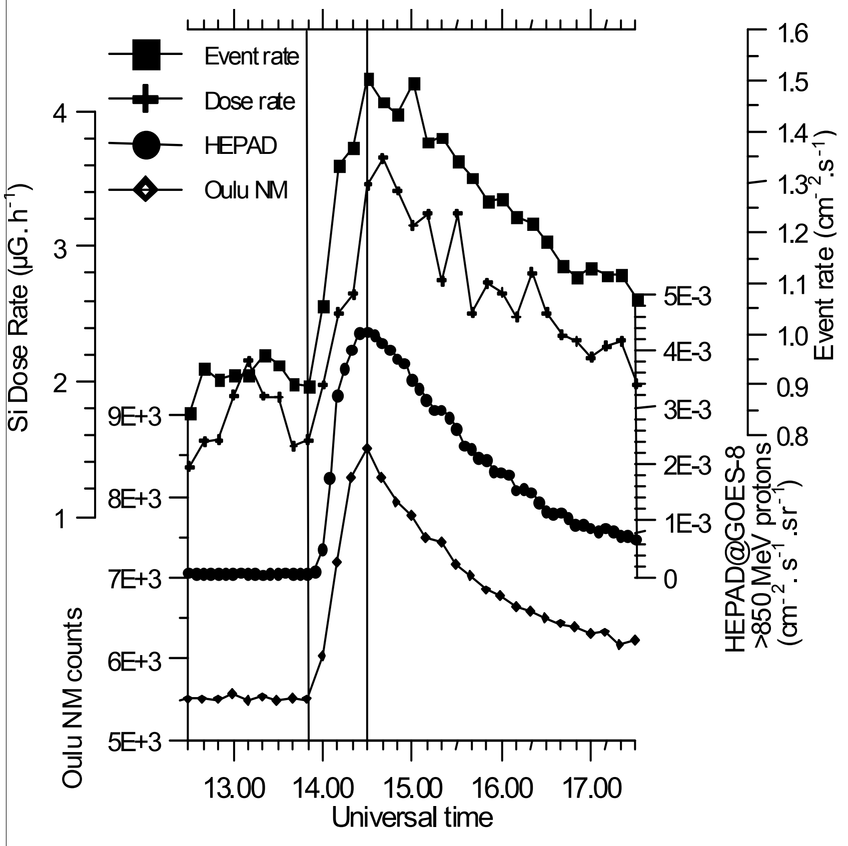
Even during weaker flare in 1989 during few hours it could exceed weakly dose from GCR by factor 2.

(for astronauts – probably fatal outside)

Dyer, 2001

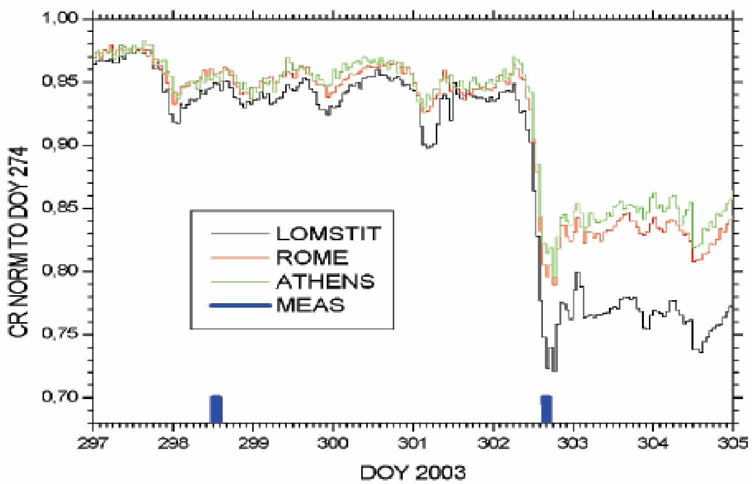
Dose is increasing during solar flare/CME acceleration of protons to high energy. From (*Spurný, F., Radiat. Protect. Dosimetry, Letter to editor, 2001*).

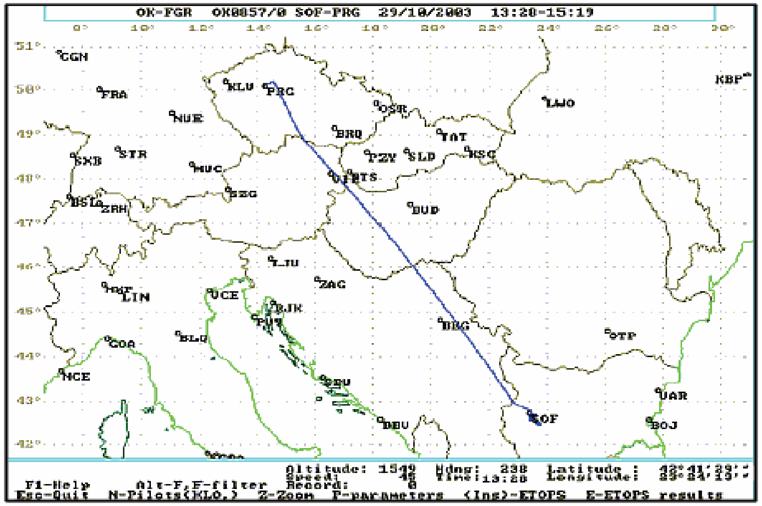


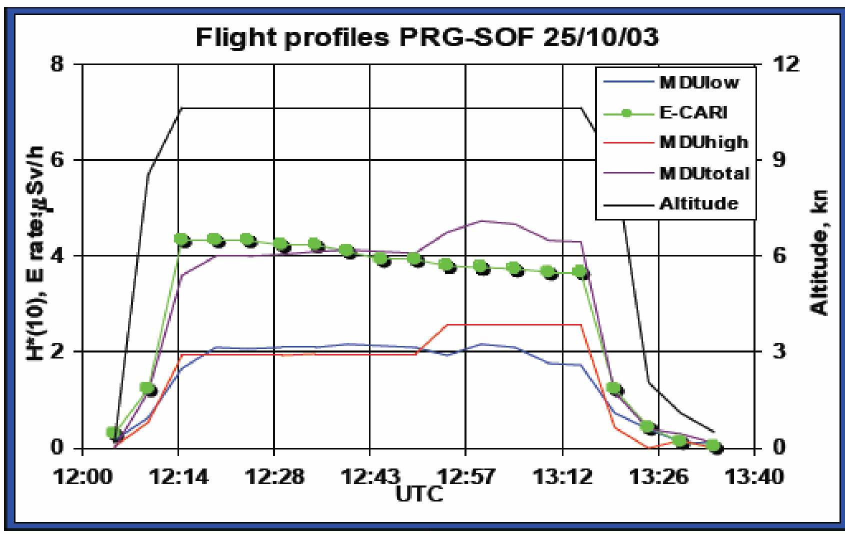


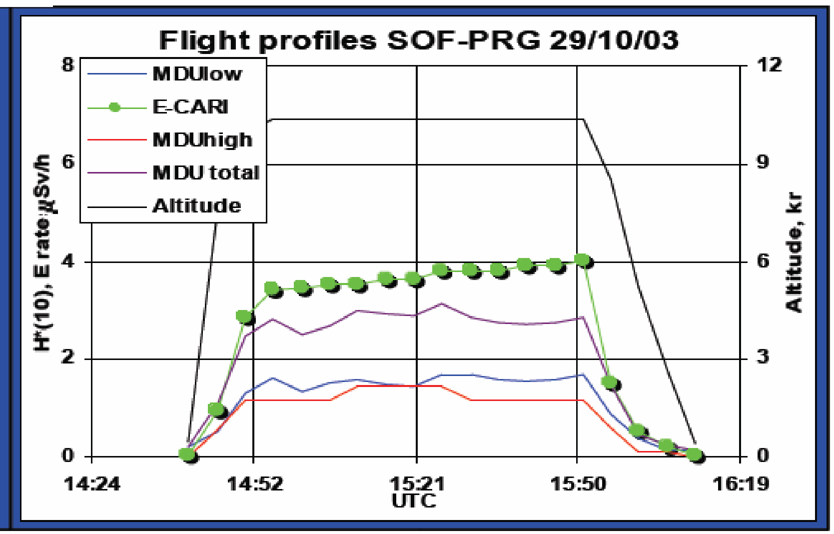
Dose is decreasing during strong Forbush decreases, one of the largests, Oct. 2003. From (*Spurný, F. et al., Space Weather, 2, S05001, doi:10.1029/2004SW000074, 2004*).

Forbush decrease after GLE 65 29/10/2003

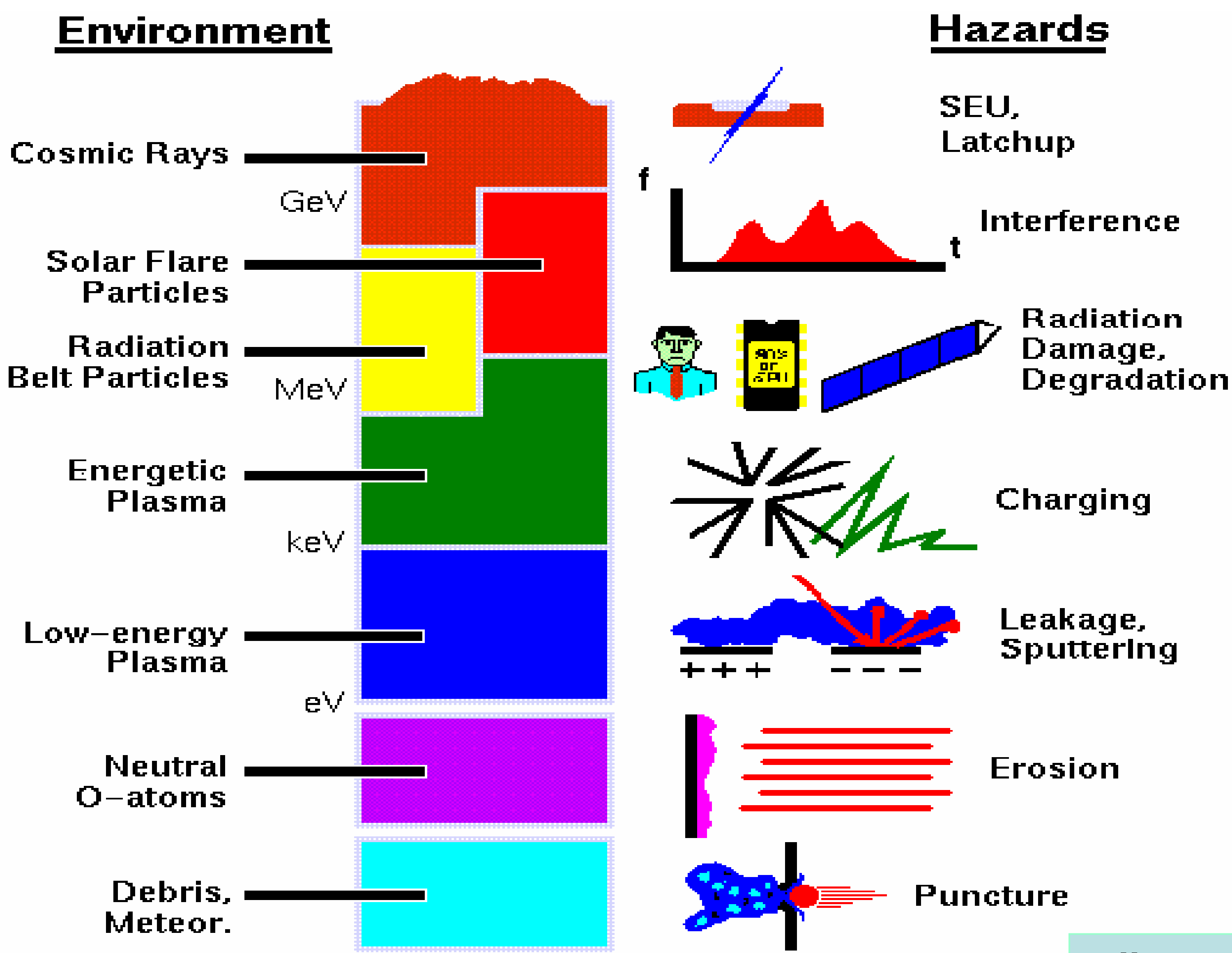








4. High energy particles and spacecraft failures.



Hilgers and Daly,1998

Effects of cosmic rays on Spacecraft and Aircraft Electronics are listed e.g. in papers

(C. Dyer and D. Rodgers, ESA WPP-155, 17-26, 1999;

E.J. Daly, ESA SP-477, xvii-xxiv, 2002 among others)

Total dose effects

Lattice displacement damage

Single event upsets (memories corrupted)

Electrostatic charging, deep dielectric charging

Interval April-June 2002 as example:

27 June 2002, Aqua, Single Event Upset, safe/hold condition, operations restored one day later

4 May 2002, DirecTV3, SCP failure

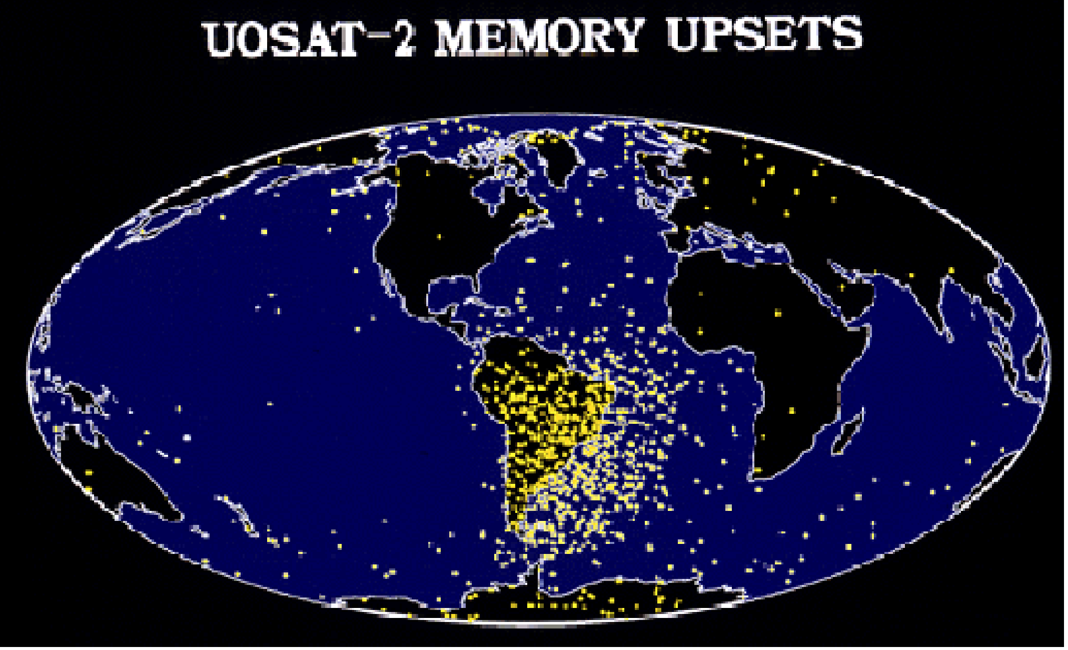
21 April 2002, Genesis, Star tracker blinded 4 times during solar storm (high energy protons)

21 April 2002, Nozomi, Hit by solar storm, loss of most communications, one instrument damaged.

Aqua,NASA 685km sol.-synchr. orbit, failure in South Atlantic

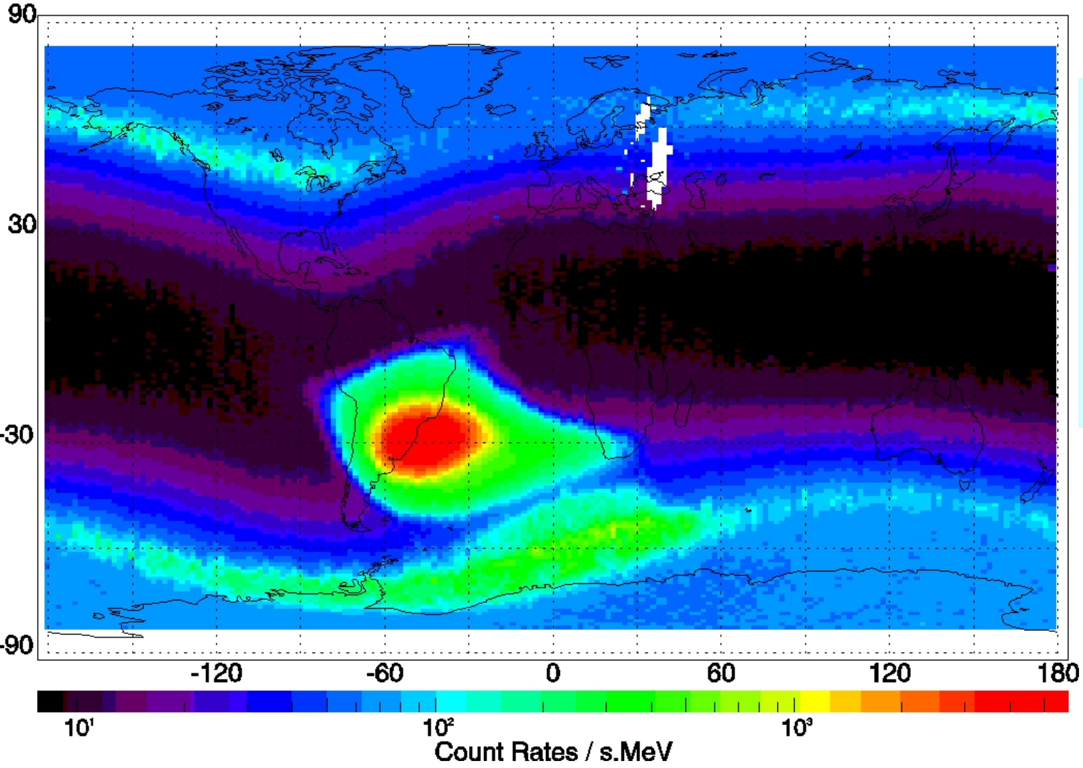
Genesis, NASA mission 1.5 mil. km

Nozomi, NASDA/ISAS, JP



Single Event Upset effects at UOSAT-2 satellite

From F. Nichitiu, 2004, http://www.lnf.infn.it/seminars/nichitiu.ppt



Map of gamma ray flux ~3-8 MeV on 500 km, CORONAS-I satellite,

From (*Bučík, R. PhD thesis, 2004 and Bučík, R. et al., Acta Physica Slovaca, 50, 267-274, 2000*).

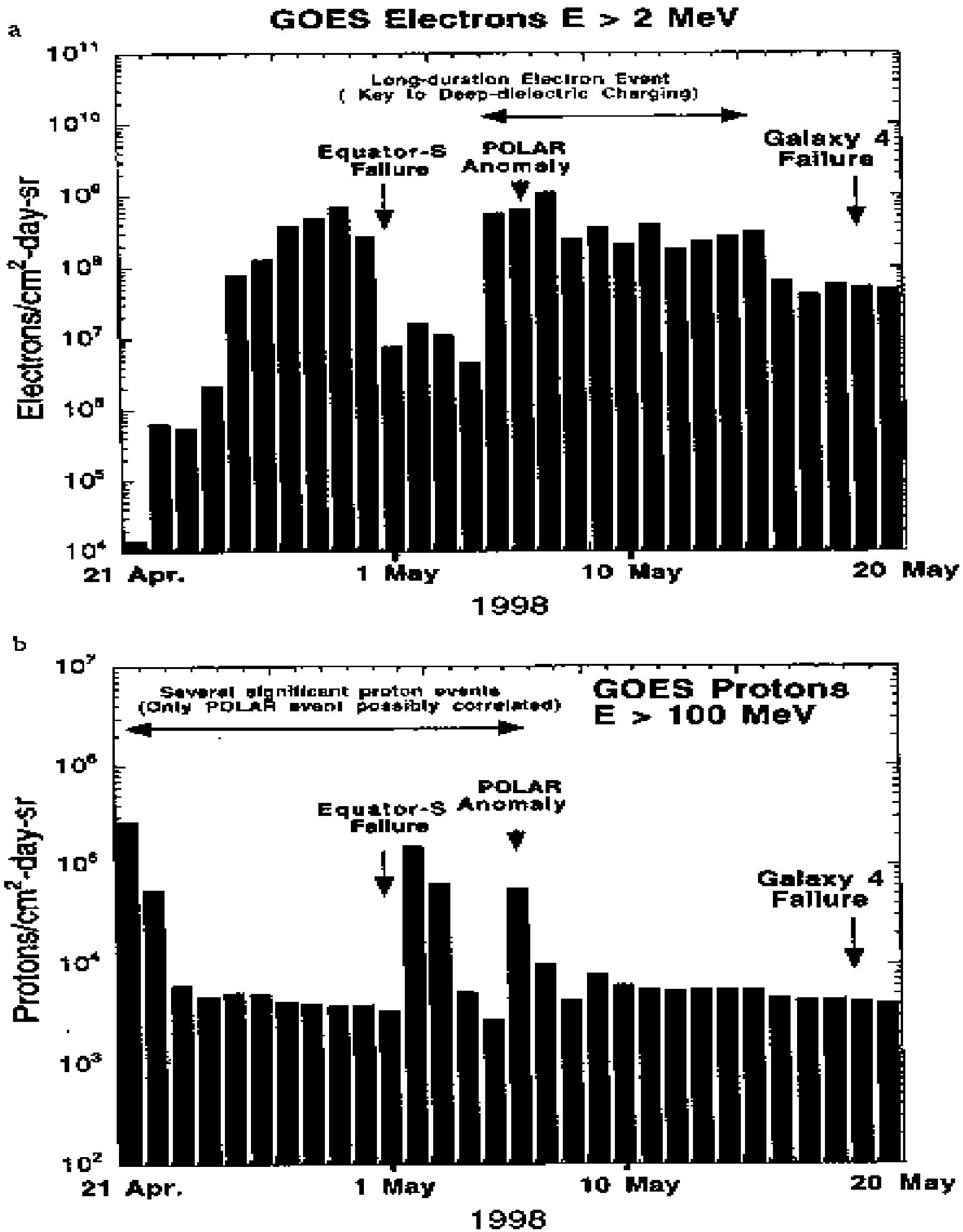


Fig. 3. a) GOES daily flux values of electrons with E>2 MeV for the period from April 21, 1998, to May 20, 1998. Dates of various spacecraft operational problems are noted including the Galaxy 4 failure on May 19. b) Similar to a) but for protons with E>100 MeV (courtesy of H. Singer).

Electrons due to their penetration ability into materials (cables, inner spacecraft system) are dangerous for satellites. Deep dielectric charging.

From (*Baker, D.N. et al., Disturbed space environment may have been related to pager satellite failure, Eos, 79, 477, 1998*)

From (*Tříska, P. et al., Ann. Geophys., 23, 3111-3113,2005*):

Magion-5 (subsatellite to Interball-auroral) showed that SPE events have immediate negative effect on solar array efficiency; step-like decreases in solar array power output are observed; cases of distinct decreases of power output can be explained by increase of RB particle flux.

Significant difference of solar array power at three subsatellites (almost same construction) at different orbits: highest rate of degradation is for auroral one (Magion-5).

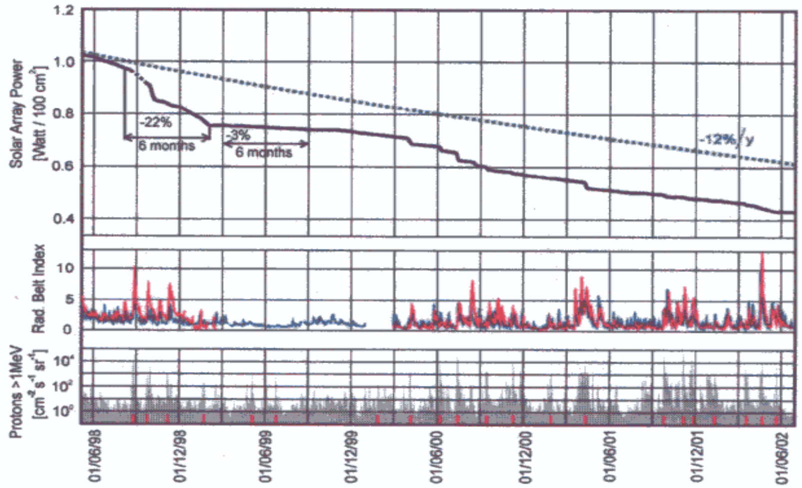


Fig. 2. MAGION-5 solar array degradation during the period from May 1998 to July 2002. The two curves in the central part of the figure show the radiation belt indices based on NOAA POES data: >30 keV (red) and the >300 keV (blue) electrons. Daily proton flux values measured by FOES-8 are shown in the lower panel. Solar proton events are denoted by red marks on the time scale. Note: most of the step-like decreases in the solar cells' output power are connected with strong solar proton events; periods with a steeper decrease in the output power correspond to periods of enhanced radiation belt indices.

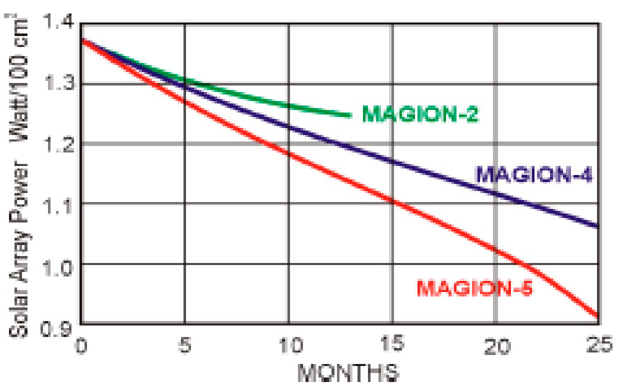
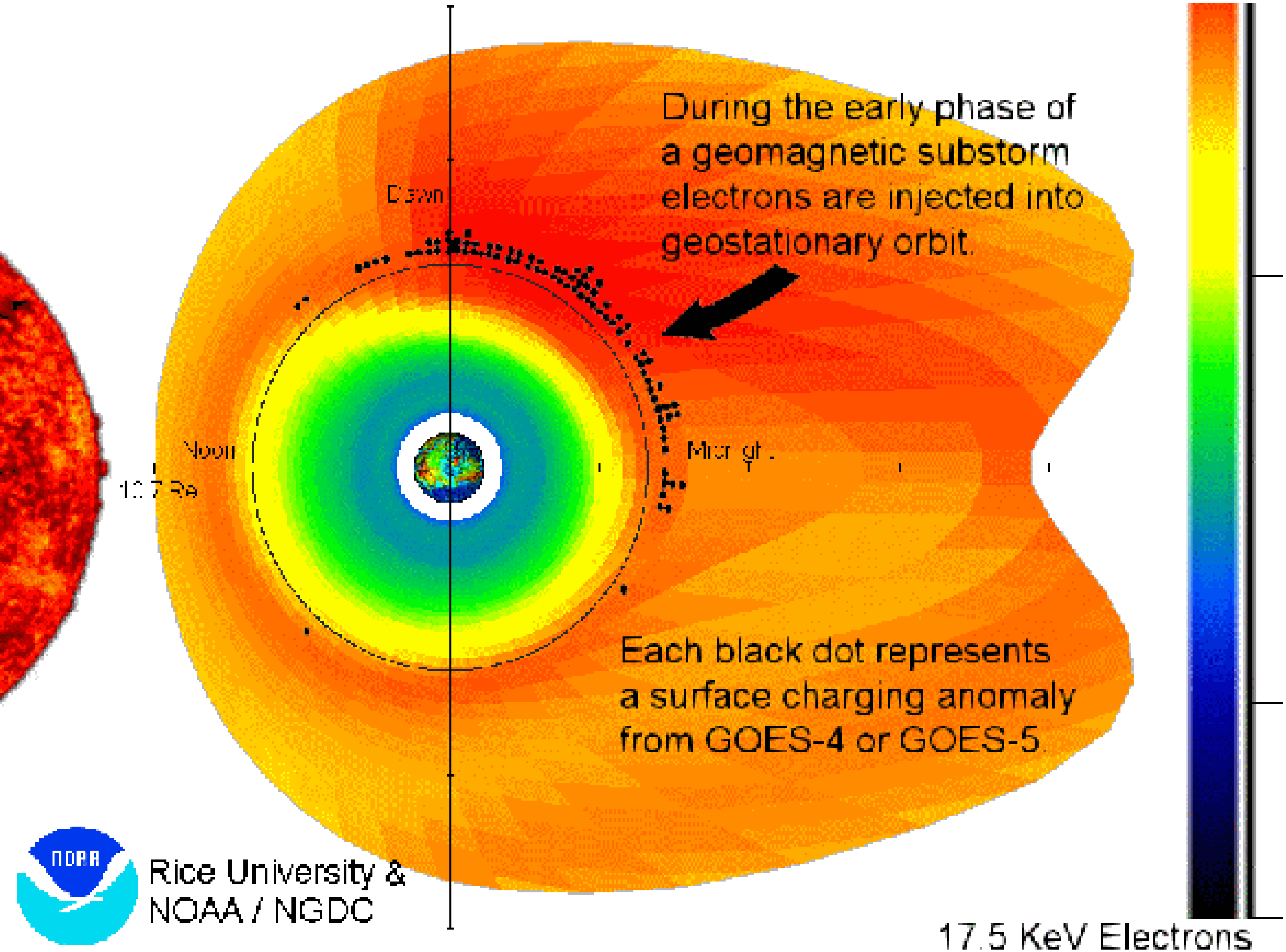


Fig. 3. MAGION-4 and MAGION-5 solar array degradation during the 25 months after launch. Most of the differences between these two curves can be explained by the effect of the radiation belts, which is more than 10 times stronger along the orbit of MAGION-5 than MAGION-4. The solar array degradation curve measured on the low-orbiting MAGION-2 (apogee 2400 km) is shown for comparison.

Surface charging anomalies occur at places where energetic electrons are injected to geostationary orbit (from Rice University and NOAA web sites).



B. INDIRECT RELATIONS OF COSMIC RAYS

TO SPACE WEATHER EFFECTS.

Can cosmic ray records be useful for space weather effects forecast?

One of most important space weather effects – ***geomagnetic storms.***

(attracting now more attention – effects on technological systems, on life

1903

DISTURBANCES IN TELEGRAPH LINES

... the world whole telegraph system was upset ...

... for several hours communication was almost completely interrupted ...

... 675 V of electricity – enough to kill a man – in the wires, without any battery connected to them ...

(cited from Nature, 5. Nov. 1903)

1989

DAMAGE IN 9 SATELLITES

... SMM dropped in altitude by 3 miles ... / ... episodes of uncontrolled tumbling ...

permanent and/or temporary disturbances in the electronic systems of 4 satellites

COMMUNICATION

... out of Hf-radio contact from southern U.S. to sites around the world ...

... California Highway Patrol messages wereoverpowering local transmissions in Minnesota ...

... undersea cables in Atlantic and Pacific oceans experienced large voltage swings ...

NAVIGATION

... U.S. Coast Guard reported numerous LORAN navigation problems ...

... ship navigation near Australia using signal from navigation satellites were impaired ...

POWER GRIDS

Long power break in Quebec, 6 Mill. people without electricity for 9 hours

Power failures in six 130-kV grids in Sweden

Disturbances in power grids of New York, Maryland, New Mexico, Arizona, California (*...but no general blackout ...*)

OTHER

... microchip production facilities in the northeastern U.S. out of operation two or more times ...

(cited from [26])

Comparison of informations about effects of strong geomagnetic storms beginning and end of last century

Similar storms in 1903 and in 1989

Dst < -300 nT

Geomagnetic storms

- One of the most pronounced effect of the changed physical conditions in near Earth space
- CME (coronal mass emissions) – occasional emissions from solar surface of 10^{12}-10^{13} kg plasma
- Compressing the solar wind plasma, IP shocks
- Selected CMEs are geoeffective ($B_z < 0$) – geomagnetic disturbances
- Compression of dayside magnetosphere
- Changes of dynamo conditions – creation of electric potentials and current systems in magnetosphere and ionosphere
- Input from SW : 10^{12} – 10^{13} W

CR and geomagnetic storm forecast. Elements of physics behind.

*CR particles have large **Λ, ρ** (mean free path, gyroradius in IMF)*

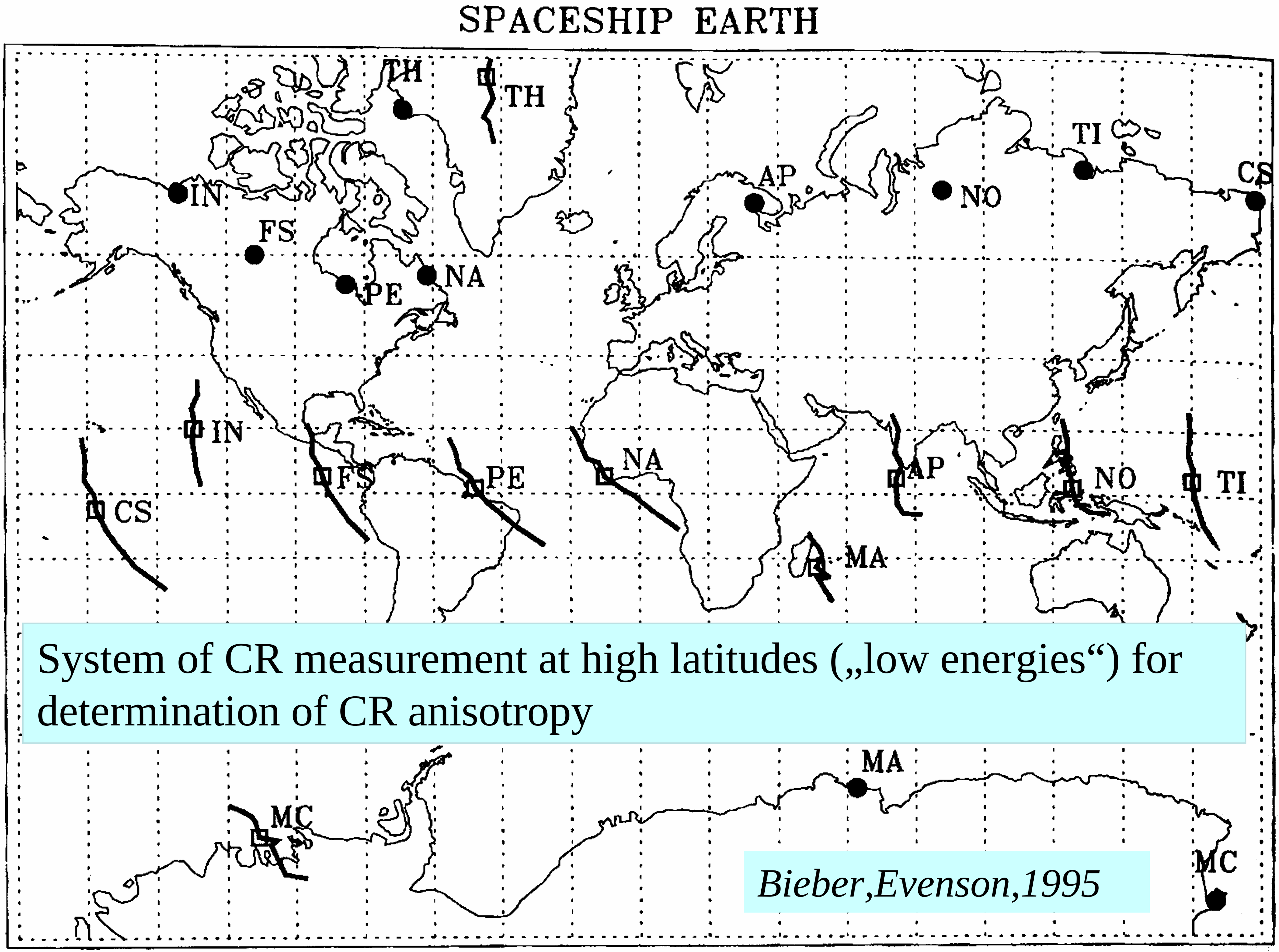
*CME is an **„obstacle“** for CR, CME affects CR anisotropy (A) due to changes of IMF* **B** *at large scale. This A is **“transmitted”** to large distances **fast** (high CR velocity).*

*At Earth CR detectors observe **(in some cases) change of A several hours before** the main disturbance with CME initiating **geomagnetic storm** appears (velocity is that of plasma in MHD, CME is at Earth’s orbit 10-20 hours after its starting time near the Sun)*

*Depending on (i) **magnetic connectivity** to the region in upstream from the shock created at the border of CME; (ii) **geometry of CME**; (iii) **velocity and direction** of the CME motion in IP space*

precursors in CR anisotropy/variability of disturbance can be seen several hours before the onset of the storm.

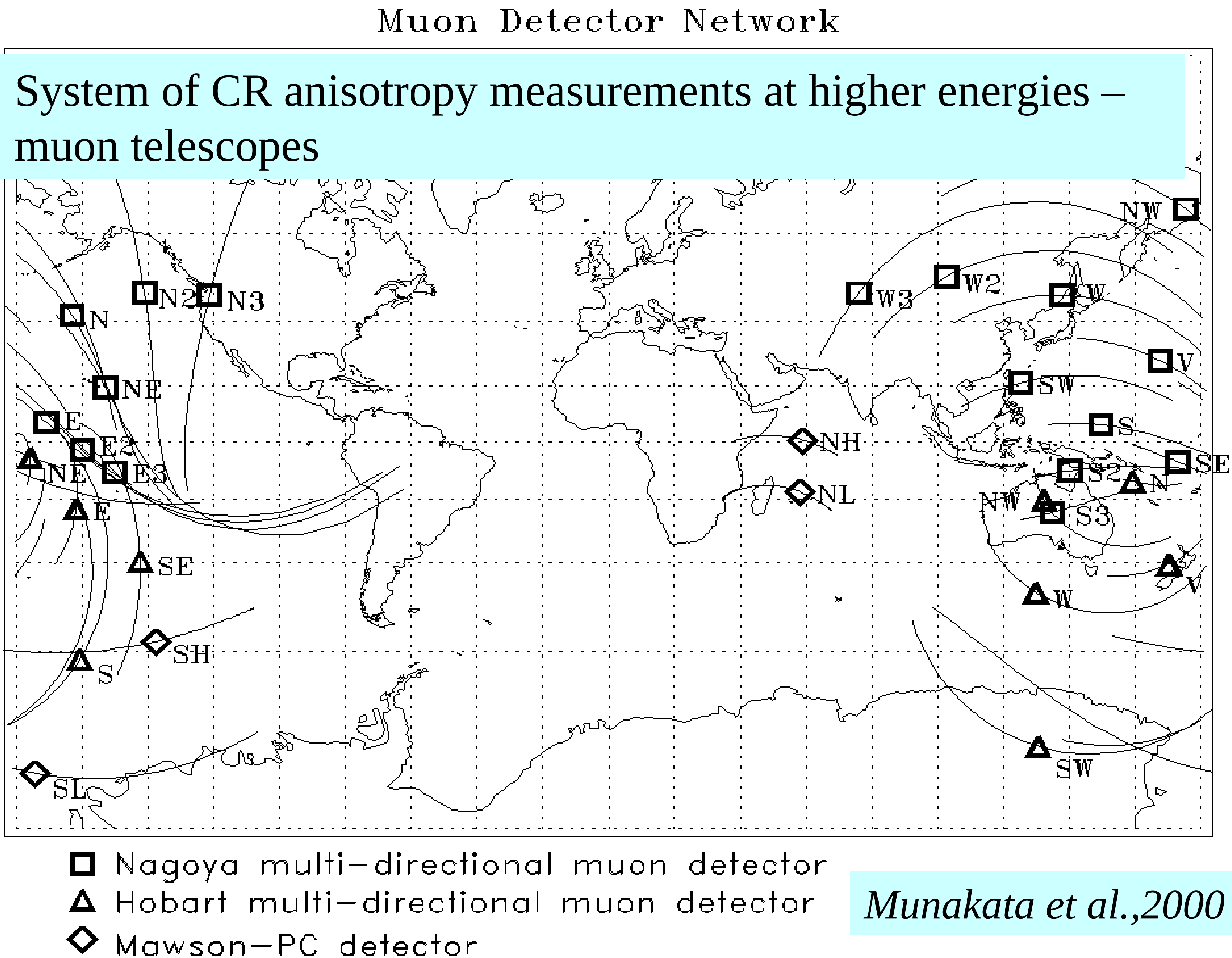
Example: statistical study indicating CR NM variability is better related to the time interval before the onset of Dst decrease than during the storm (3 NM, years around solar activity maxima (Kudela et al, ICRC 1995)



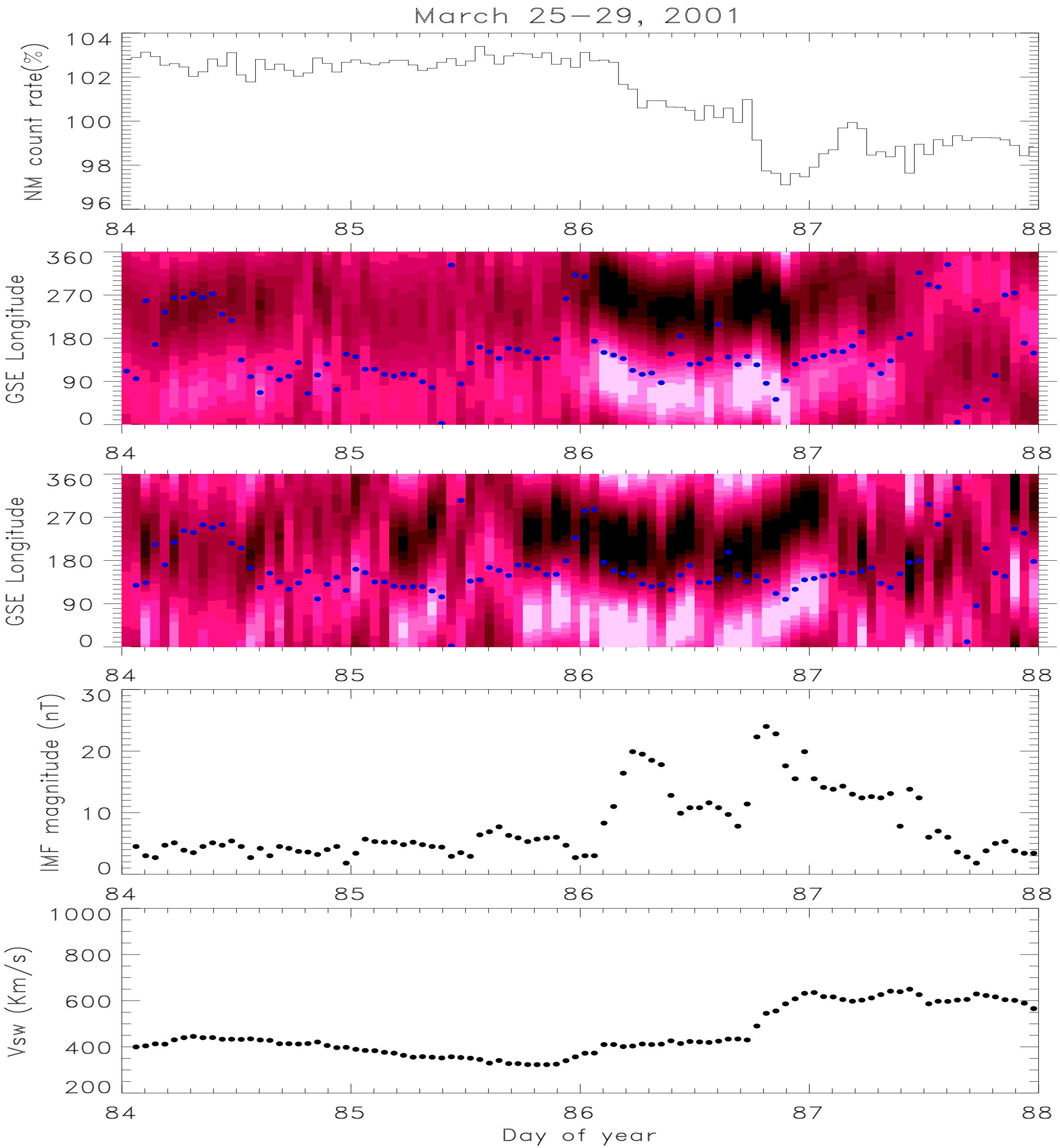
System of CR measurement at high latitudes („low energies“) for determination of CR anisotropy

Bieber,Evenson,1995

System of CR anisotropy measurements at higher energies – muon telescopes



Munakata et al.,2000

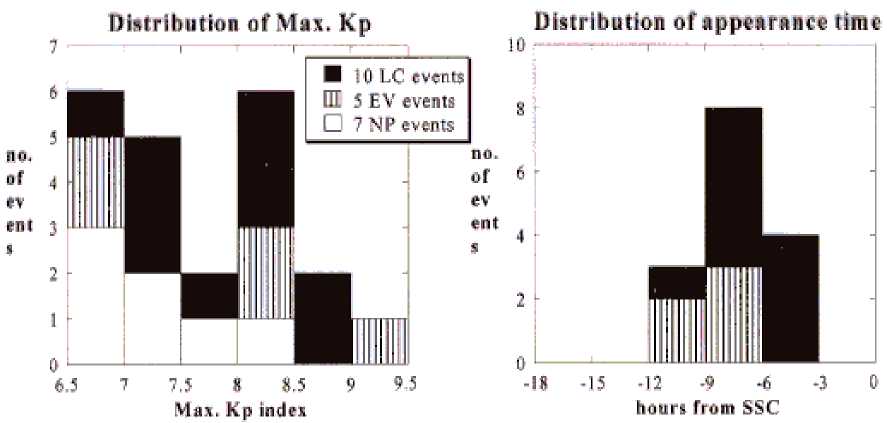


CR anisotropy detected by network of high latitude NMs and by MTs (decrease – dark).

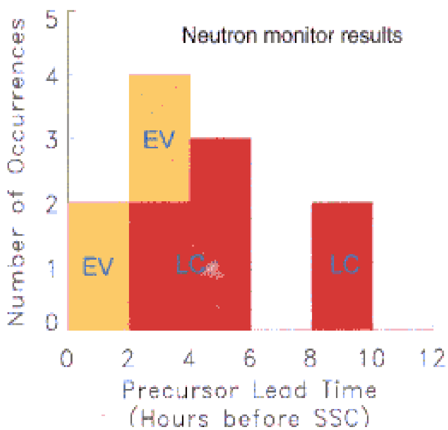
*Onset is **before the main phase of geomagnetic storm**. For MTs it is ealier.*

Munakata et al, 2001

Loss-cone (LC) and Enhanced variance (EV) precursors at MTs (upper, *Munakata et al., 2000*) and at NMs (lower, *Belov et al., 2001*) for major geomagnetic storms identified in (*Gosling et al., 1990*)



MT



NM

Precursors of CR before the strongest geomagnetic storms.

Recently: *Dorman, L.I. et al.* (*Forecasting of radiation hazard, Adv. Space Res., 2005*) suggested to use very high energy (GeV and above) particle signatures in real time (now NMs provide at many stations 1 min resolution data) as alerts for Solar Radiation Storm – FEP events (S5 to S3 scale according to NOAA clasification).

The alert is based on total count measurements and measurements of multiplicities (different distribution for different energy spectra of primary particles) and on their change during the interval of few minutes.

This approach is additional to those indicating evolution of cosmic ray anisotropy as observed by neutron monitors and muon telescopes few hours before the onset of geomagnetic storms (*reviews e.g. in papers by Storini, M. et al, EGU 2006, Kudela, K. et al., Space Sci. Rev. 93, 153-174, 2000*) among others with citations of original works on the subject.

New installation: MUSTANG in Greifswald, Germany.

References (books).

1. Longair, M.S. High energy astrophysics, vol. 1, Particles, photons and their detection, Cambridge University Press, second edition 1992, reprinted with corrections 2004

2. Dorman, L.I. Cosmic ray in atmosphere and underground, Kluwer Academic Publishers, Dordrecht, 2004

3. Hillas, A.M. Cosmic Rays, Pergamon Press, Oxford, 1972.