External Exposure to Natural Radiation: Sources, Dosimetry Methods and their Calibration, Results of some Experimental Studies

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- **General Principles of Radiation Protection**
- **Sources of external exposure to natural radiation, typical dose values:**

➢ **Space sources:** **space, near Earth orbits, aircraft altitudes, Earth's surface**

➢ **Terrestrial radiation:** **World overview (UNSCEAR 2000), Czech Republic, regions with elevated levels of background**

- **Dosimetry methods; Calibrations**

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Some examples of experimental results:

- **INRNE/NPI collaboration:** **measurements at Sofia, and high-mountain stations,**
- **Onboard aircraft exposure:** **international activities, own measurements 1991-1999, and after 2001, MDU series, common onboard results, extreme solar events**
- **Onboard spacecraft exposure:** **calibrations in HECP beams, onboard measurements with TLD's (common) and LET spectrometer, MDU data-comparison with aircraft**

Radiation Protection – 1

Goal: **Protection of persons and human being against harmful effect of ionizing radiation**

Effects:

- **Deterministic – characterized by a threshold**
- **Stochastic – no dose threshold, probability increases with dose – LNT concept**

Radiation protection would:

- **to exclude the possibility of deterministic effects**
- **to limit the stochastic effects at the level as low as reasonably achievable**

Radiation Protection – 2

Quantities and Units

Absorbed dose $D = (d\varepsilon/dm)$

Organ dose $D_T = (\varepsilon_T/m_T)$

Equivalent dose $H_{T,R} = w_R \,.\, D_{T,R}$, resp.

$H_T = \sum_R w_R \,.\, D_{T,R}$

Effective dose $E = \sum_T w_T \,.\, H_T$

Effective dose – principally not measurable quantity

Operational quantity:

Dose equivalent $H = Q \,.\, D$, where Q – quality factor;

Ambient dose equivalent $H^*(d)$

Personal dose equivalent $H_p(d)$

For whole body exposure *d = 10 mm*

Radiation Protection – 3

Justification - final effect of the activity leading to an exposure would be positive

Optimization - to keep the exposure as low as achievable

Limitation - not to exceed limits

LIMITS (ICRP 60)

Application	Occupational	Public
Effective dose	20 (50) mSv	1 mSv
Equivalent dose in lens of the eye	150 mSv	15 mSv
skin	500 mSv	50 mSv
hands and feet	500 mSv	-

Radiation Protection – 4

Limits, Sv:

- **aircraft –general limits of occupational exposure**
- **Spacecraft crew (NCRP 142):**

Period	Organ		
	BFO	Eye	Skin
Career	1.0	4.0	6.0
Annual	0.5	2.0	3.0
30 days	0.25	1.0	2.5

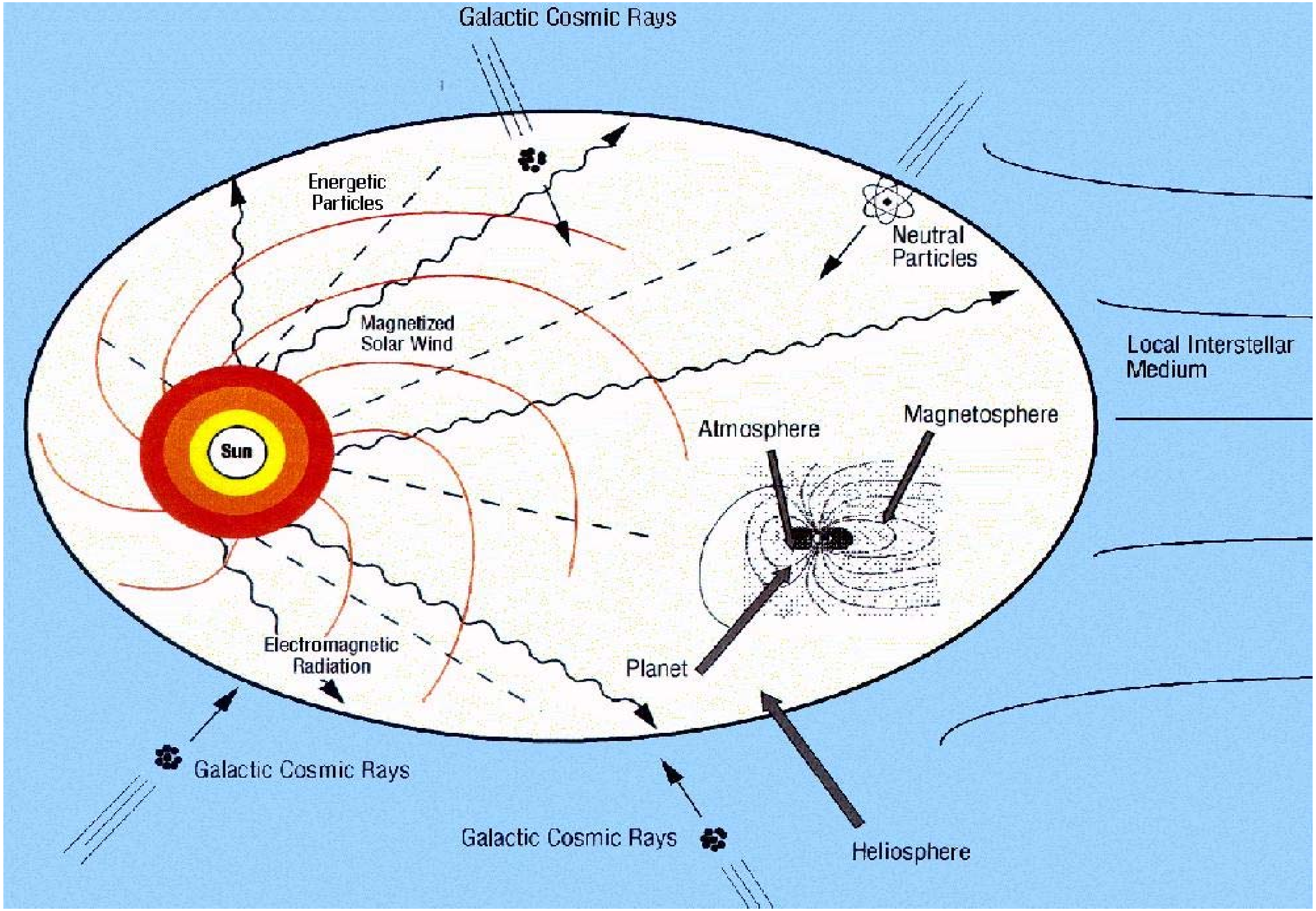
Whole body exposure, Career, Sv

Age	25	35	45	55
Male	0.7	1.0	1.5	3.0
Females	0.4	0.6	0.9	1.7

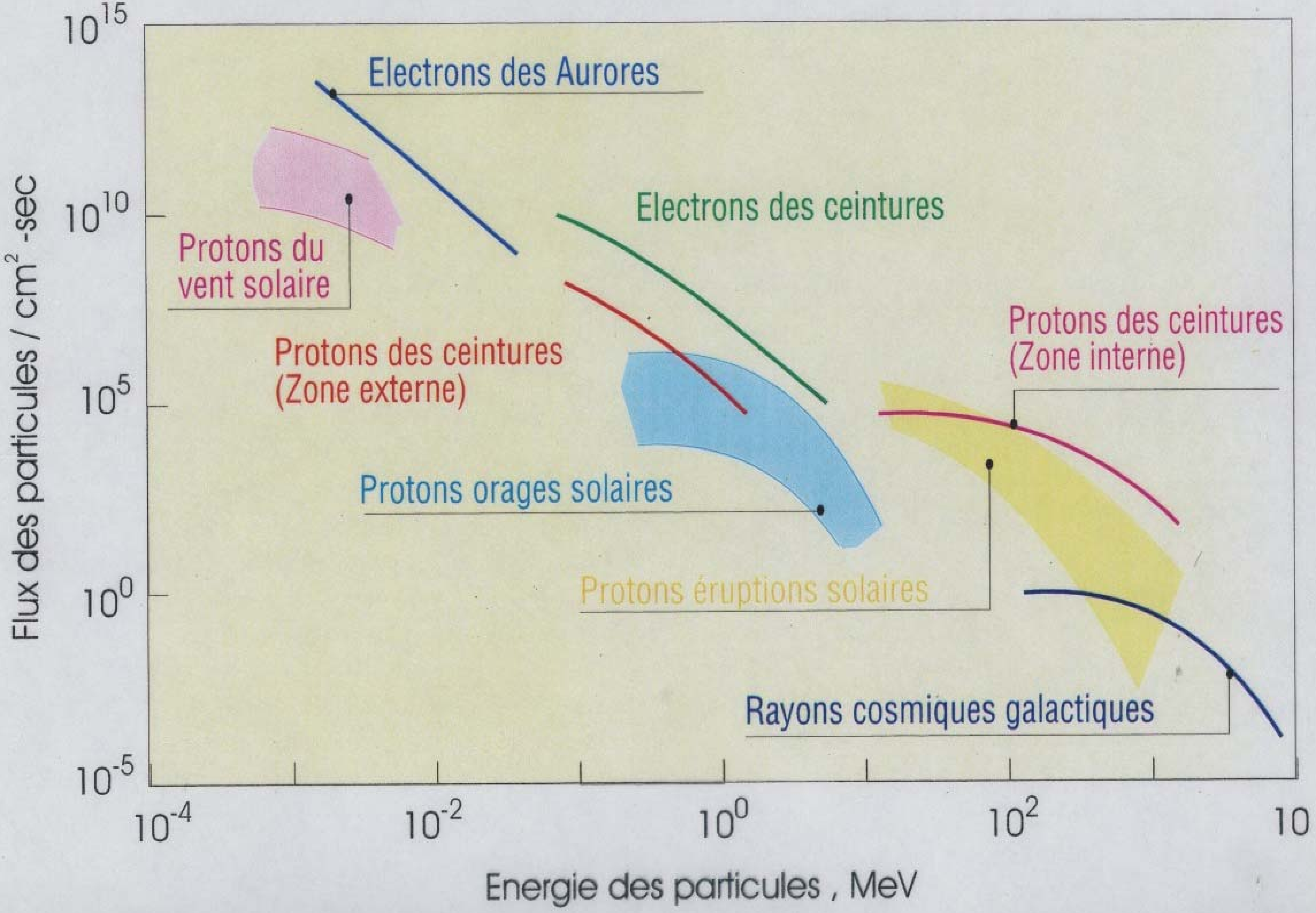
External exposure from space radiation sources

Space outside of Earth’s atmoshere

Cosmic radiation - Heliosphere



Les rayonnements cosmiques



Cosmic Radiation Dosimetry- General

Radiation Dosimetry – energy above several MeV, therefore main sources (origin, composition, spectra, particularities:

- **Galactic cosmic radiation**
- **Solar cosmic radiation** - solar flares
- **Radiation belts** – external, internal; South Atlantic Anomaly (SAA)!

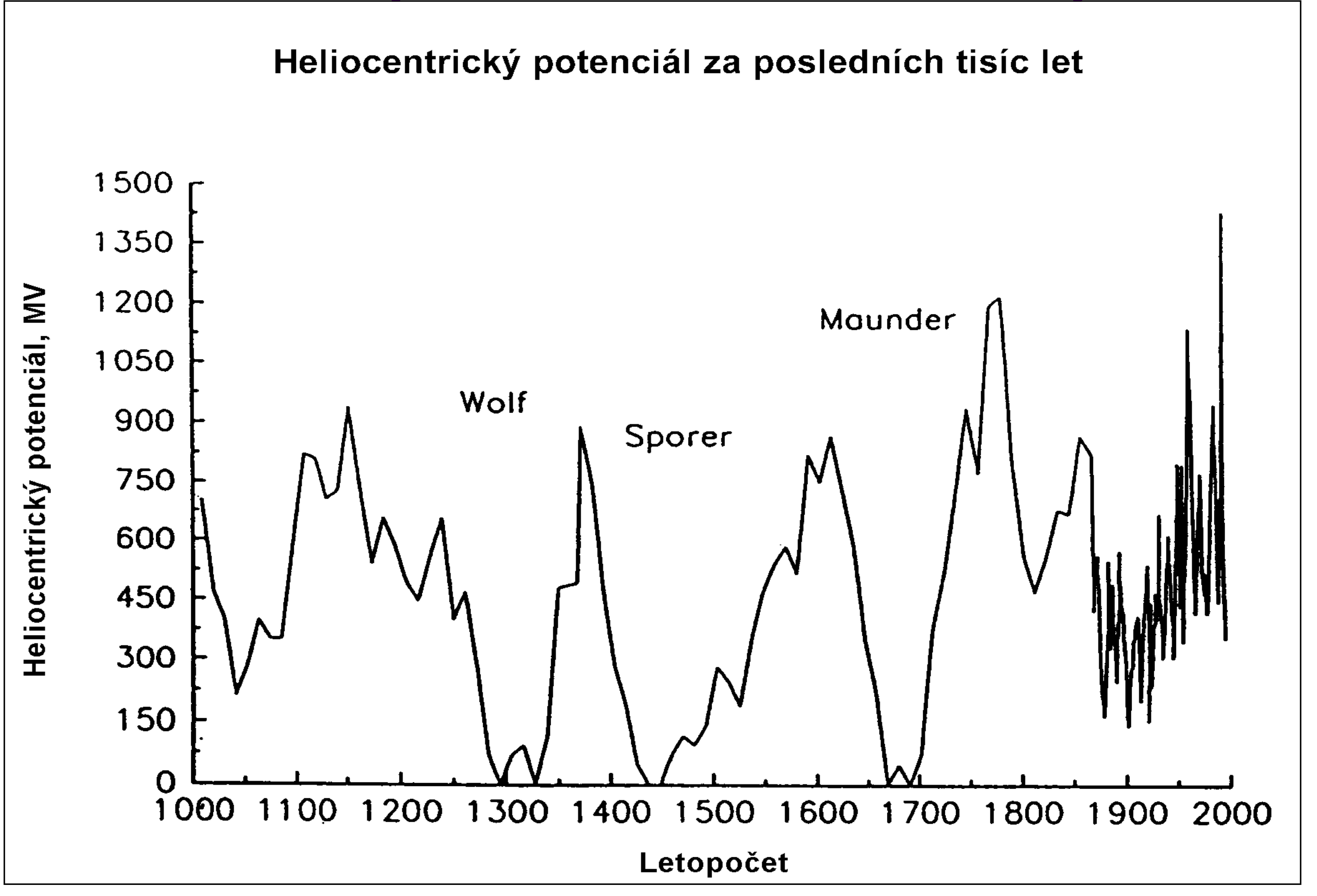
Influences:

- Solar cycle variations
- geomagnetic cut-off

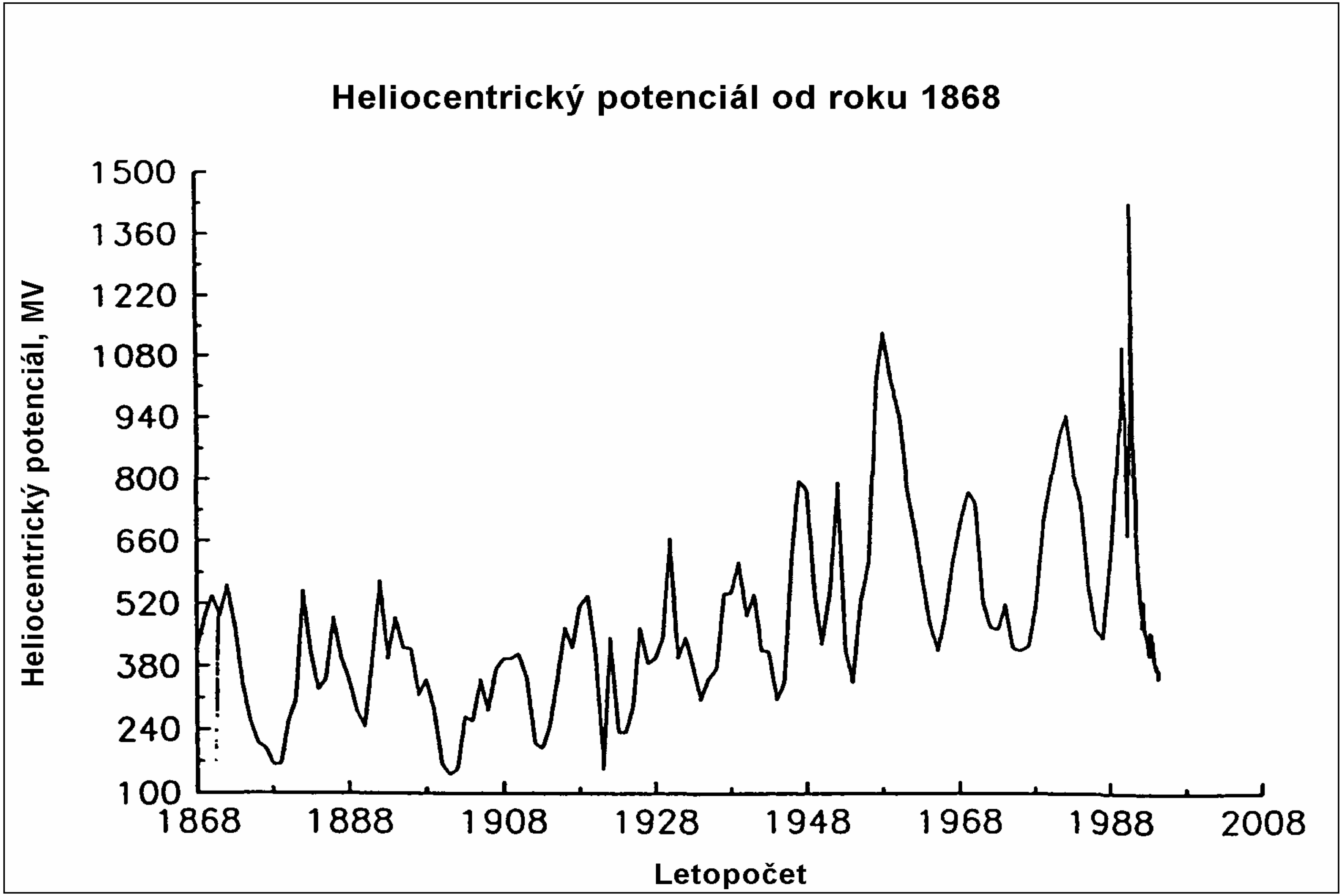
NEAR-EARTH EXPOSURE SOURCES OF THE COSMIC ORIGIN

Component ⇒ Property ⇓	Galactic	Solar	Radiation belts
Origin	Deep Space	Sun	Earth's trapped
Composition	86% p, 12% He, up to U	99% p	p, e^-
Energy	$\leq 10^{20}$ eV, $\Phi \sim E^{-2.6}$	variable, >1 GeV rare	p <100 MeV, $e^- < 1$ MeV
Distribution	isotropic	variable, flares	inner, ~3000 km, outer, ~22000 km
Particularity	solar modulated	intensity nor energy predictable	South Atlantic anomaly (SAA)
H*(10) in open space	0.4 – 1.2 Sv per year	< 10 Sv, mostly much lower	p(SAA) < 4 Sv/y, $e^- \sim 10^5$ Sv/y

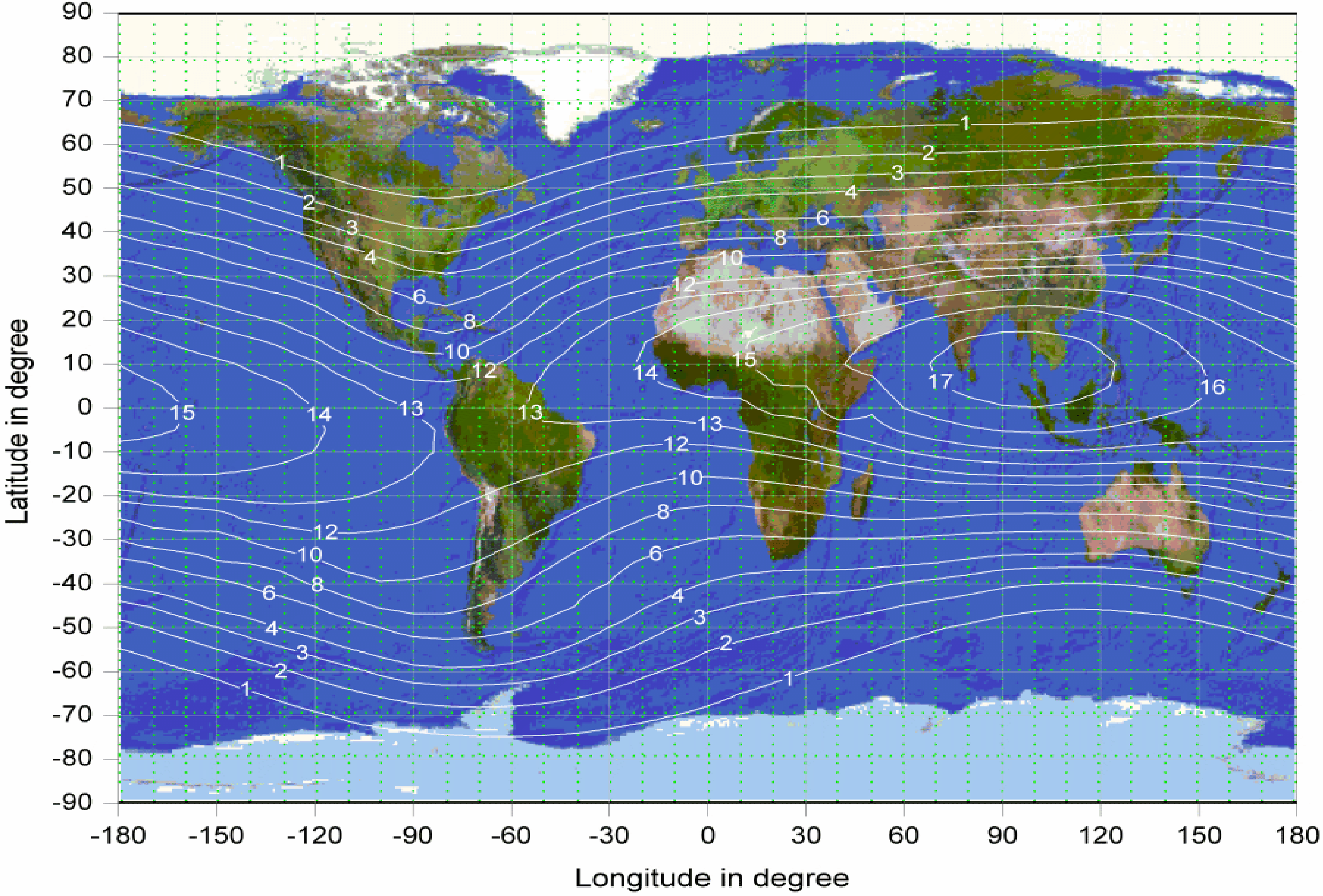
Heliocentric potential - last 1000 years



Heliocentric potential – since 1868

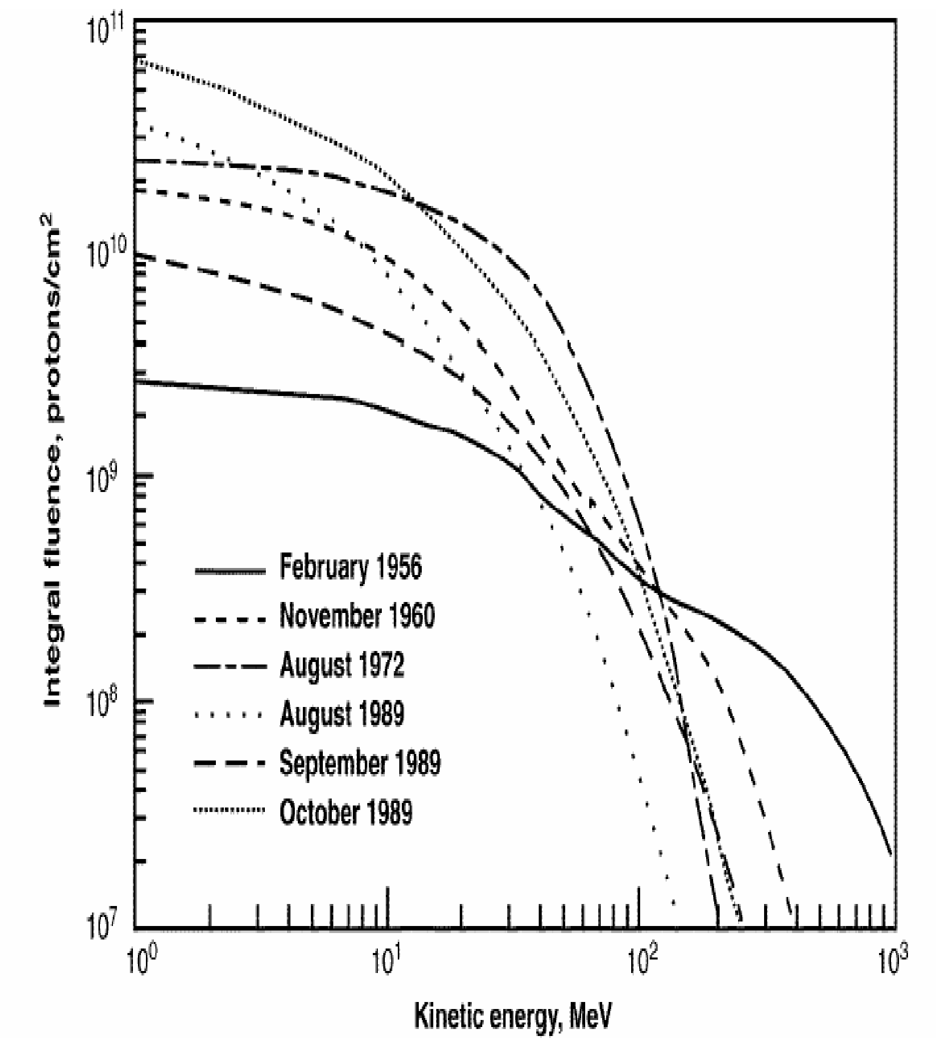


Vertical Cosmic Ray Cut-off Rigidity in GV

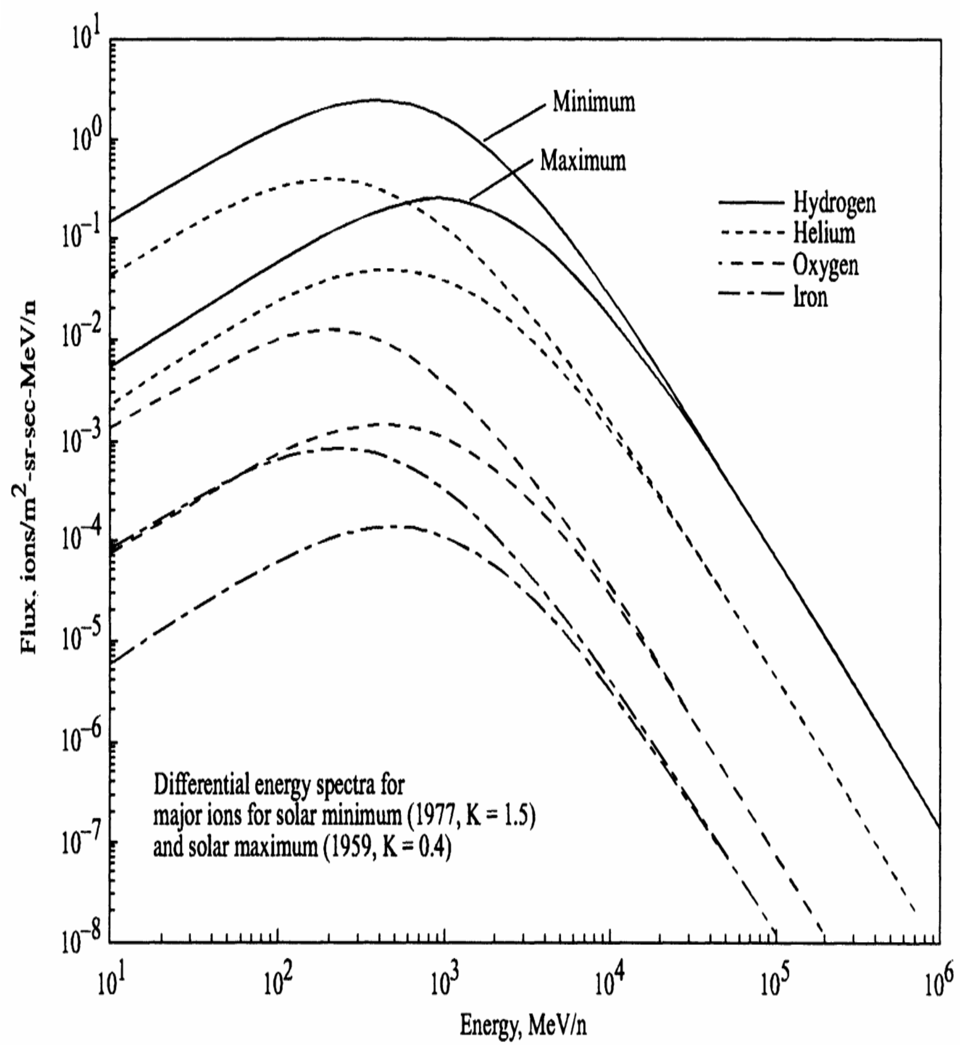


Integral energy spectra

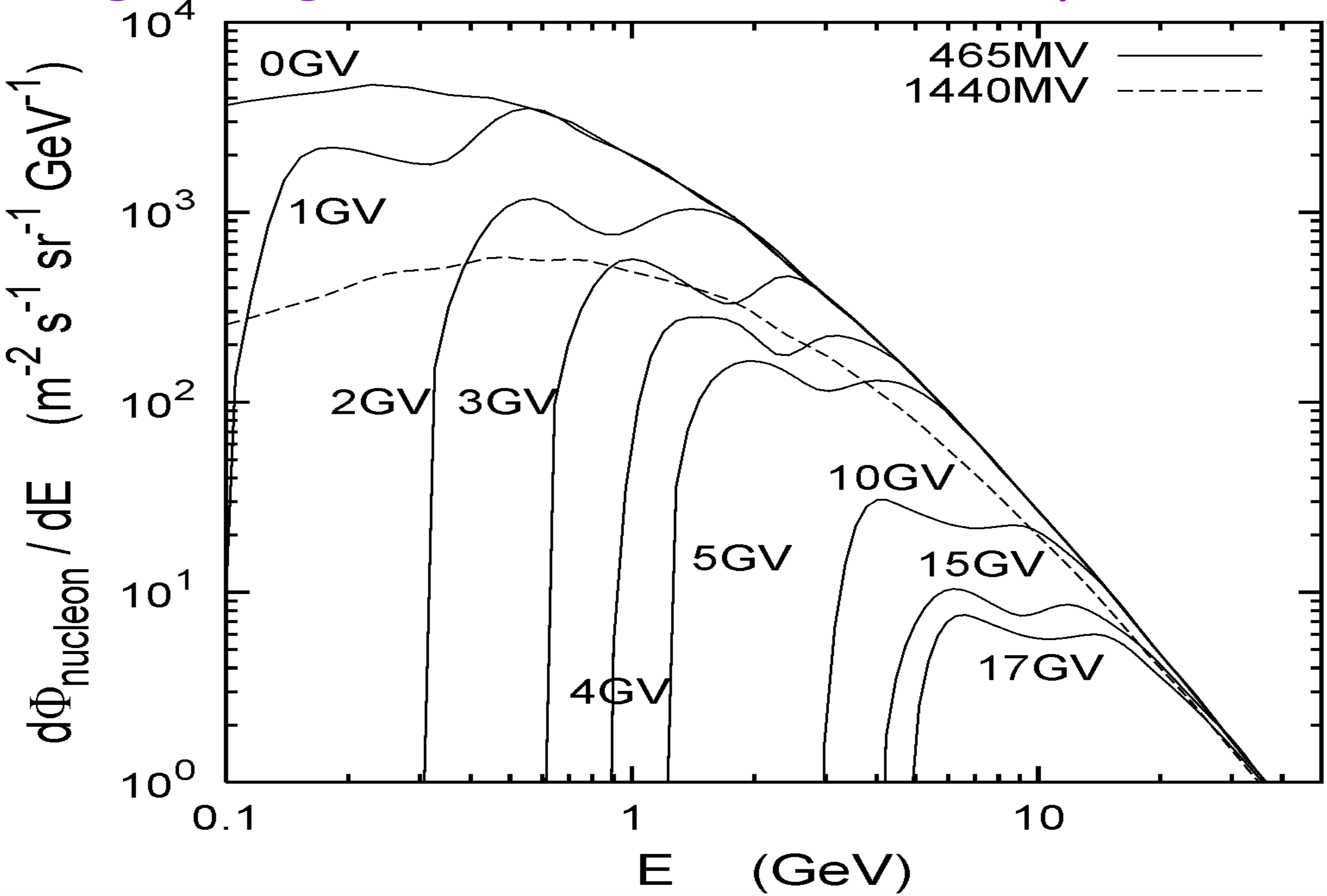
'worst' SPE



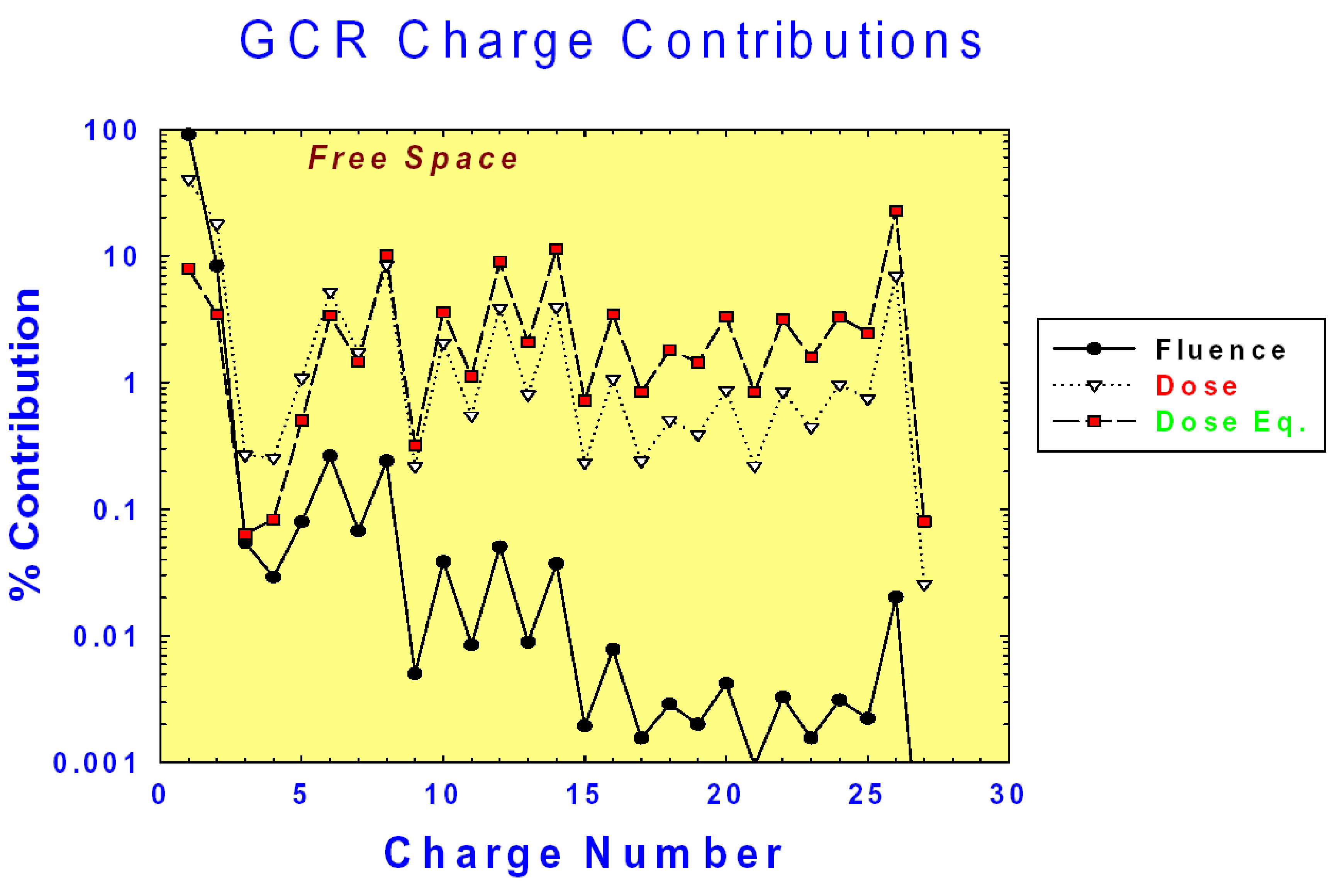
GCR



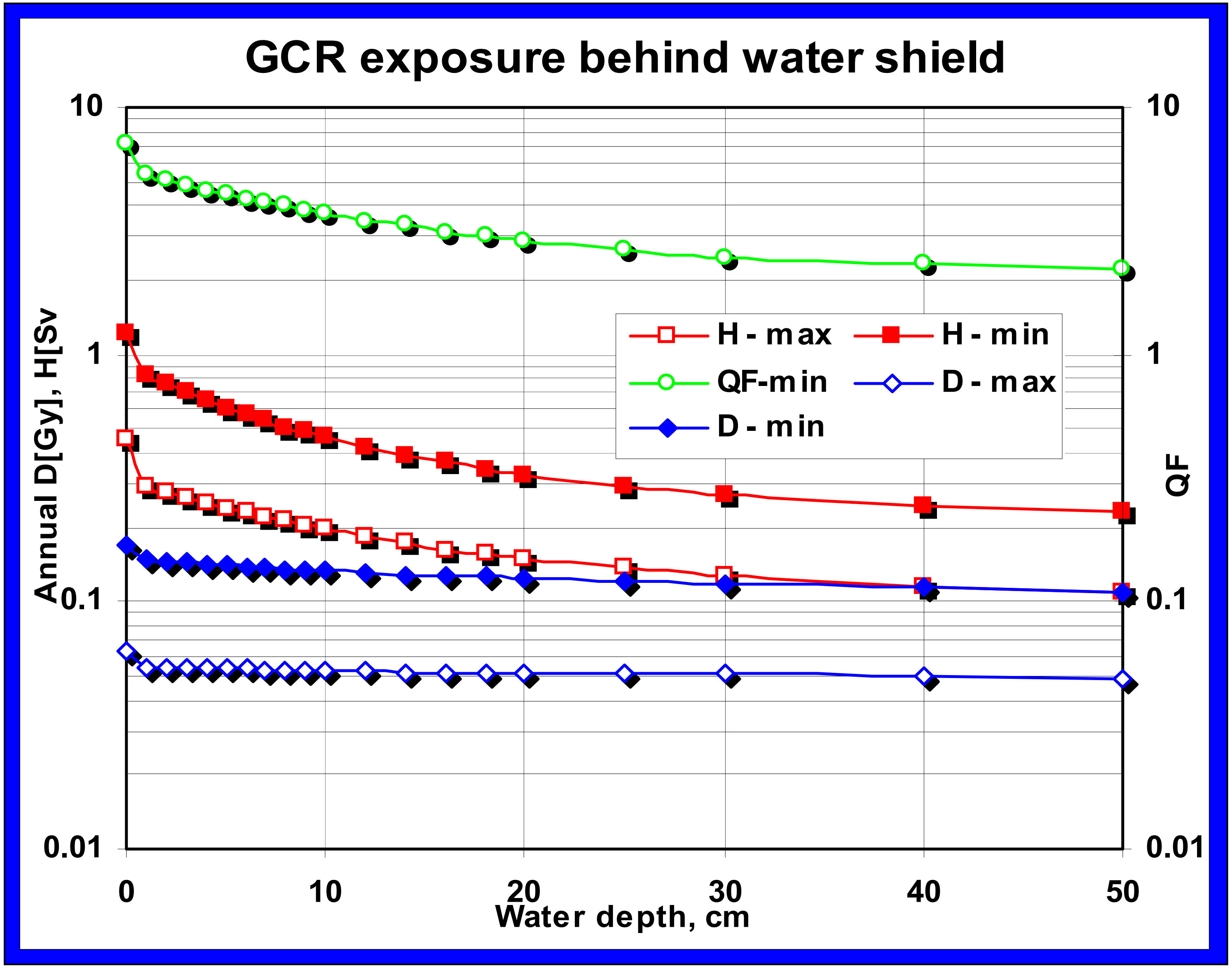
Influence of solar activity and geomagnetic cut-off on GCR spectra



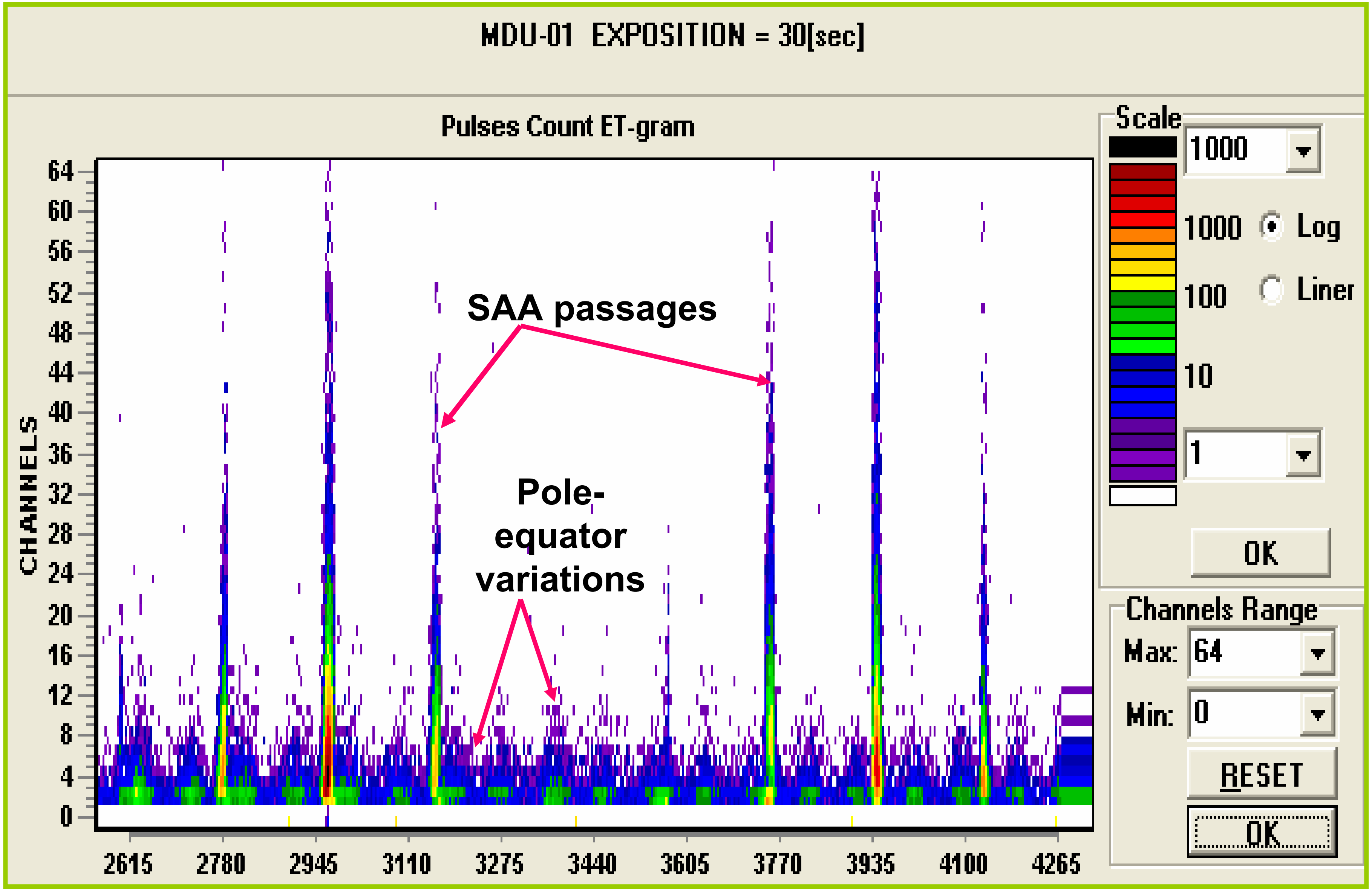
Contribution of Different GCR Particles to Fluence, Dose and Dose Equivalent



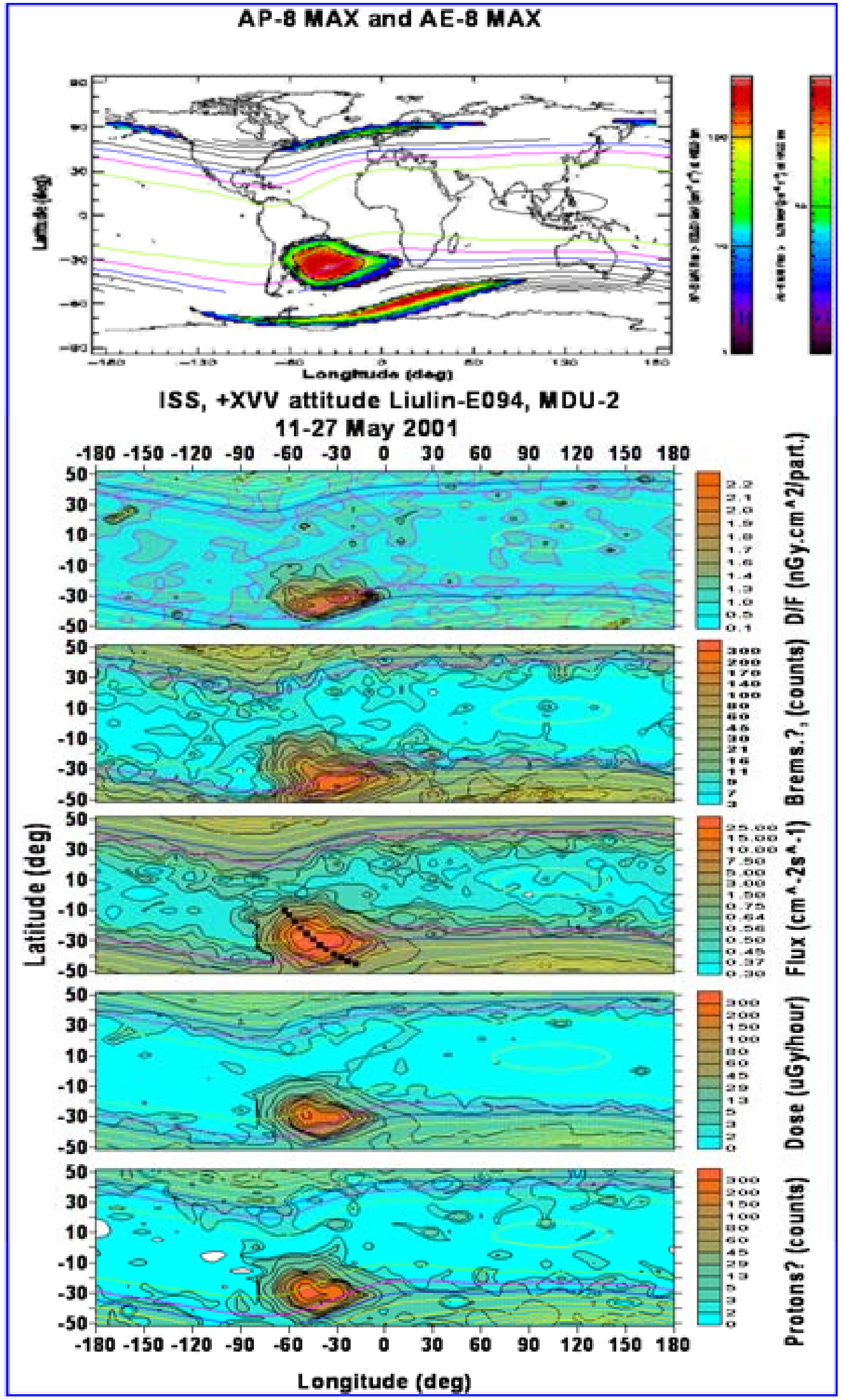
GCR exposure – influence of SA and the shield thickness



Exposure variations due to geomagnetic position as registered by Liulin



Comparison of Liulin-E094 data with AP-8 MAX and AE-8 MAX models

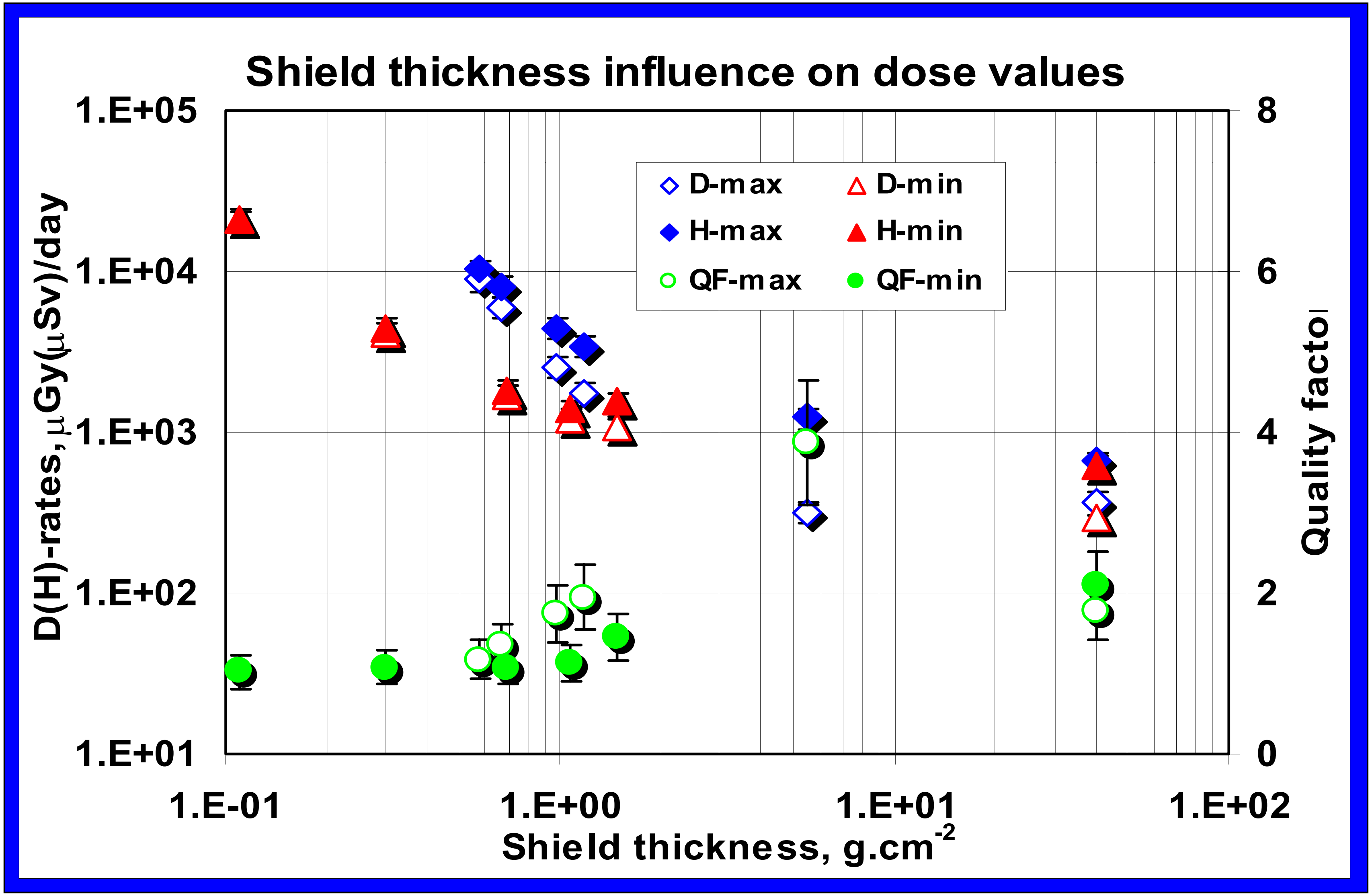


H-rates on a circular orbit due to radiation belts protons[1), shield 1 $g.cm^{-2}$

Orbit height	H-rates, Sv/day	for orbit angle		
km	0	30	60	90
445	0	0.014	0.008	0.007
2780	8.00	3.90	1.95	1.65
5550	1.25	0.55	0.28	0.24
8350	0.20	0.083	0.042	0.036

[1) **Electrons stopped by ~ 0.3 $g.cm^{-2}$ of a shield**

Dose and dose equivalent rates outside MIR station as measured with TLD and TED

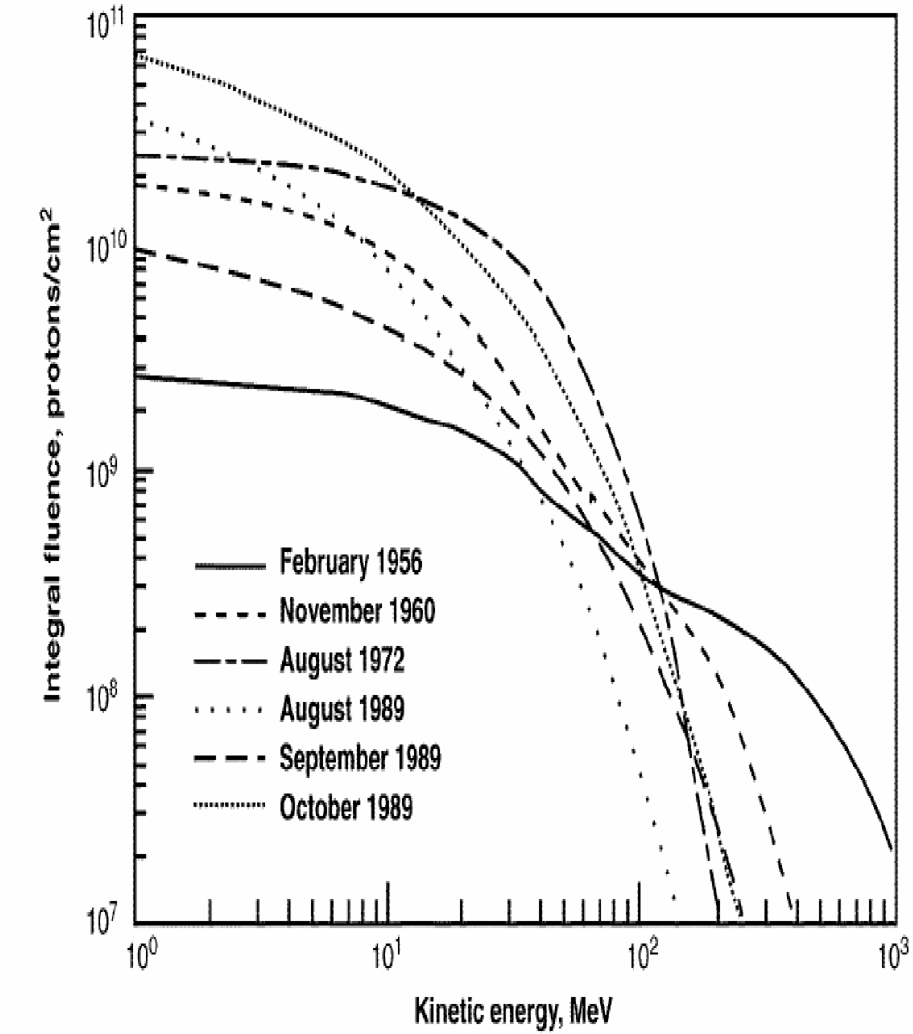


Contribution of SAA and/or GCR to the total onboard exposures – some of results obtained, 1996 - 1998

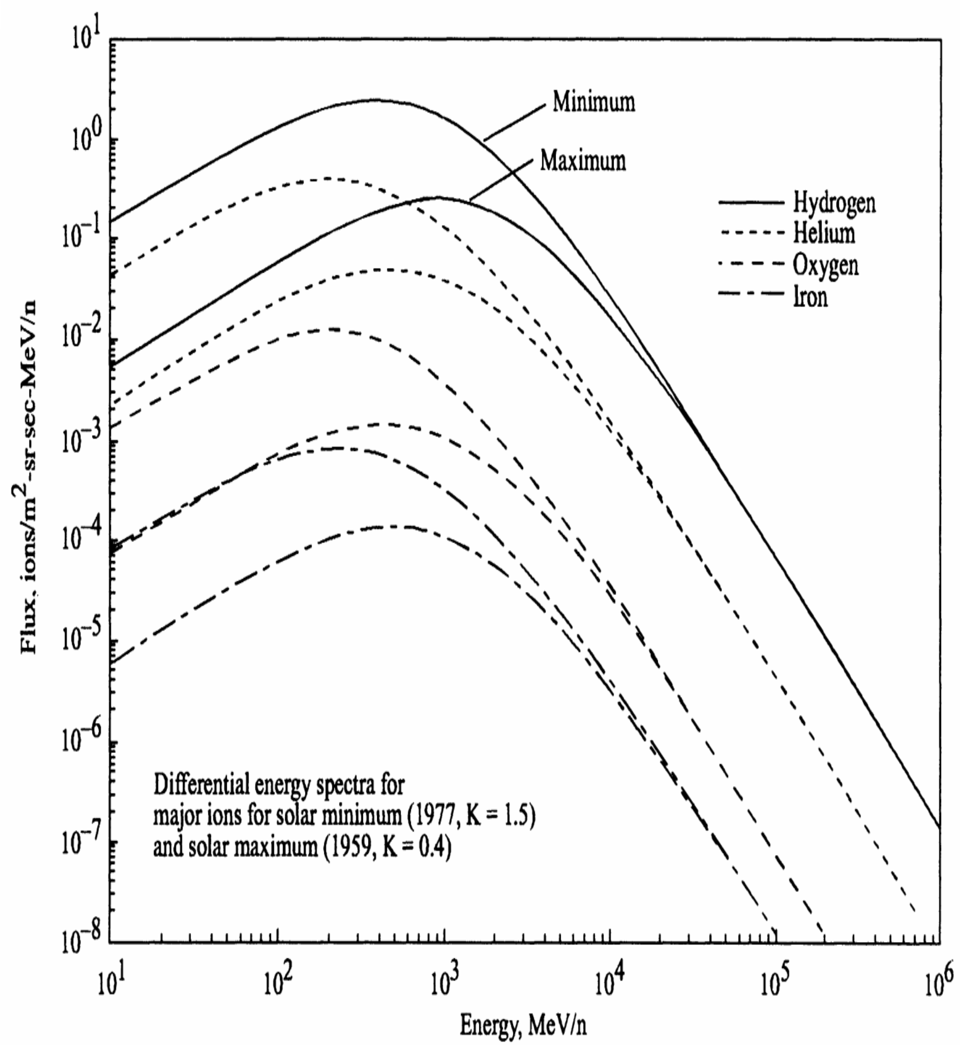
Method	Dose, µGy/d			Dose equivalent µSv/d		
	SAA	GCR	Total	SAA	GCR	Total
TLD	150	150	300	-	-	-
Si-spectr.	121	126	247	157	443	600
TEPC	240	135	375	418	439	857

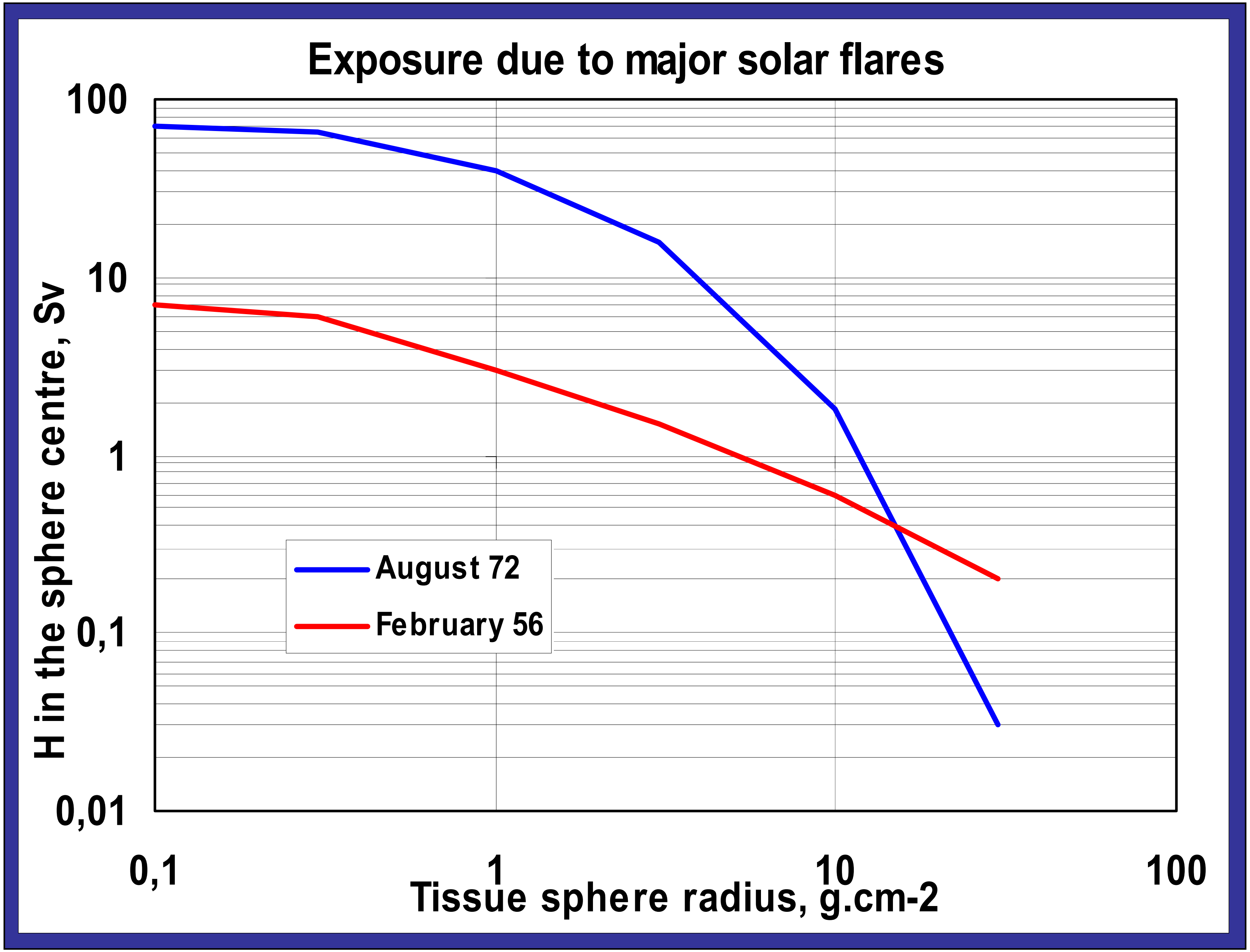
SPE - energy spectra

'worst' SPE



GCR





Exposure due to major solar flares
100
10
1
0,1
0,01
H in the sphere centre, Sv
August 72
February 56
0,1
1
10
100
Tissue sphere radius, g.cm-2

BFO doses from GCR (1977 solar minimum) and/or SPE; shield 10 $g.cm^{-2}$

GCR Sv/year	Open space	0.59
	Moon	0.29
	Mars	0.12
GCR Sv	Mission to Moon (190 days)	0.18
	Mission to Mars (947 days)	0.92
SPE*); Sv	Open space	1.3
	Lunar surface	0.6
	Mars surface	0.25

*) worst scenario – GLE 23/05/56 with 10times higher flux than that of GLE of 29/09/89

Further remarks

- **Variability inside spacecraft** – factor more than 1.5 for D, a little less for H
- **EVA** – dose rates 4 to 10 times higher than inside (attention SF, SAA and less shielded area)
- **Solar flares:**

➢ 09-10/89 – excess ~ 36 mGy (4 months of "usual")

➢ 10-11/03 – excess in total 9 mGy

(attention for EVA , SAA and less shielded area)

- **Neutrons (secondary particles):**

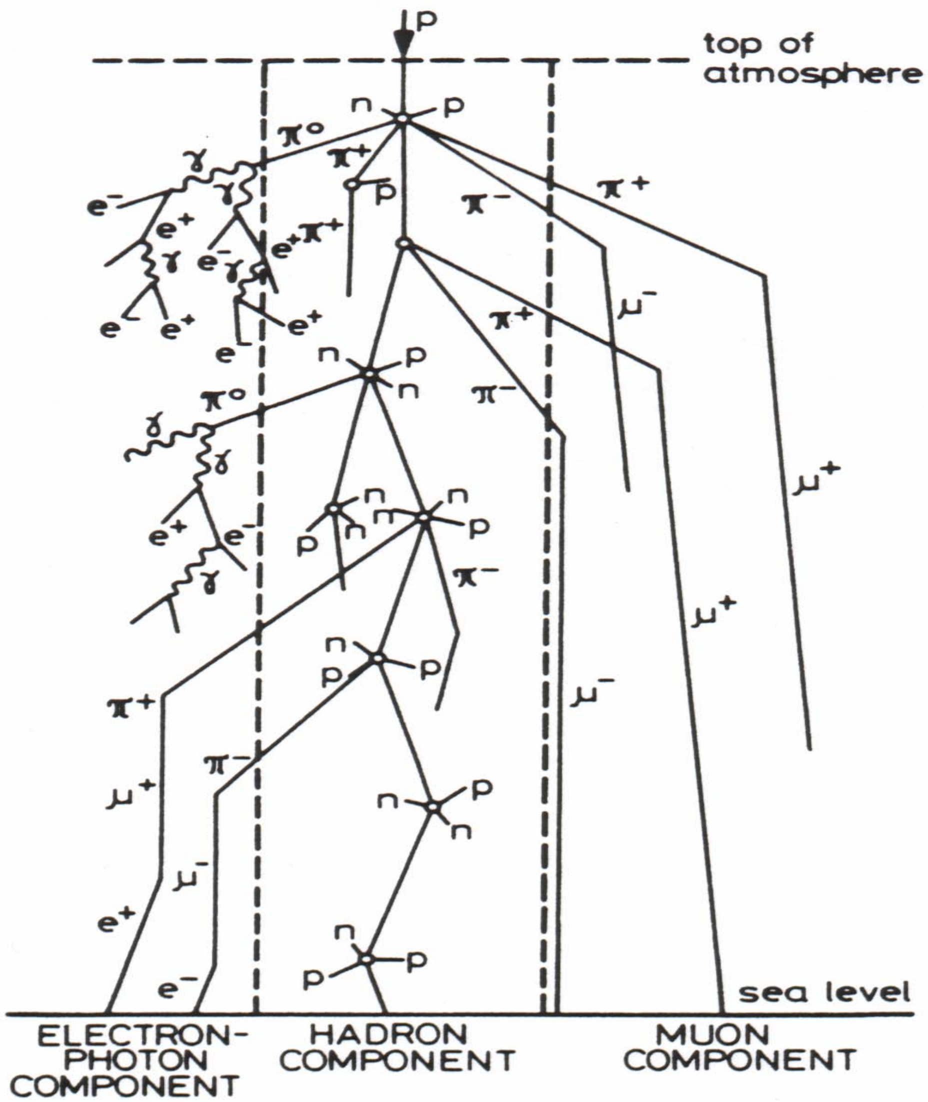
previous estimations – 15 to 25 % of total H,

now – 30 to 50 %

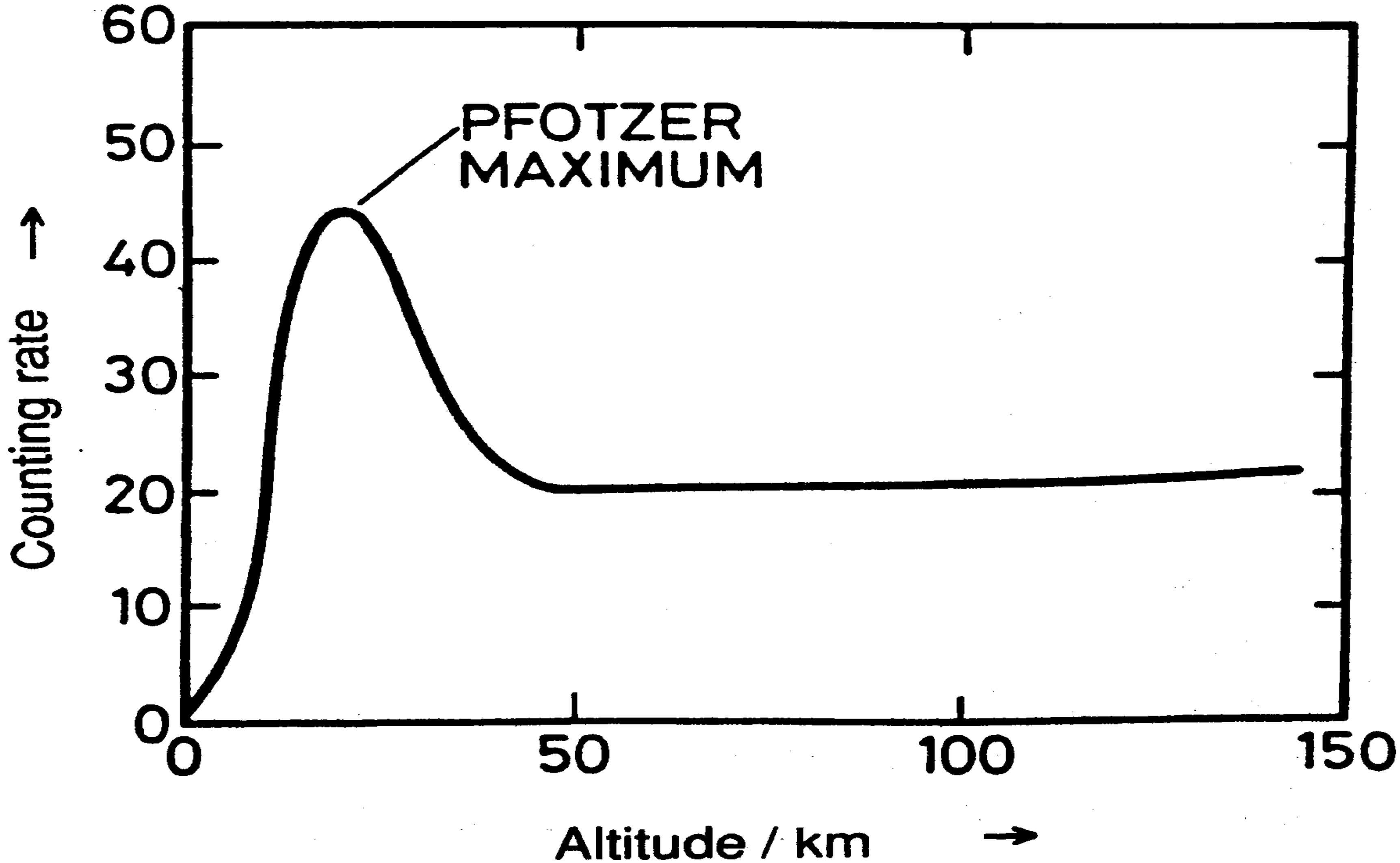
External exposure from space radiation sources

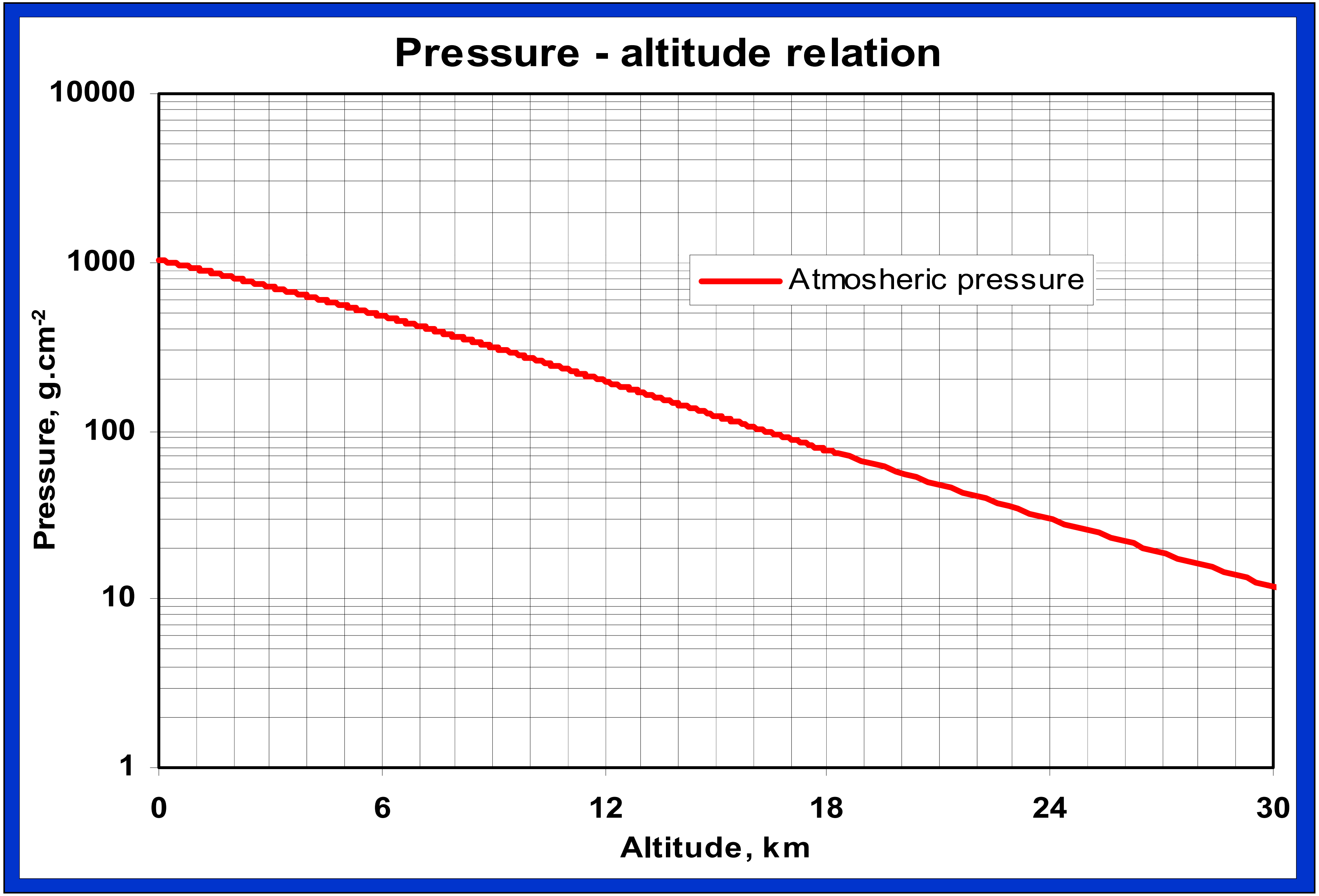
Transmission through Earth’s atmoshere, onboard aircraft exposure

Cosmic ray transmission through atmosphere



“Dose” rate (a.u.) as a function of altitude





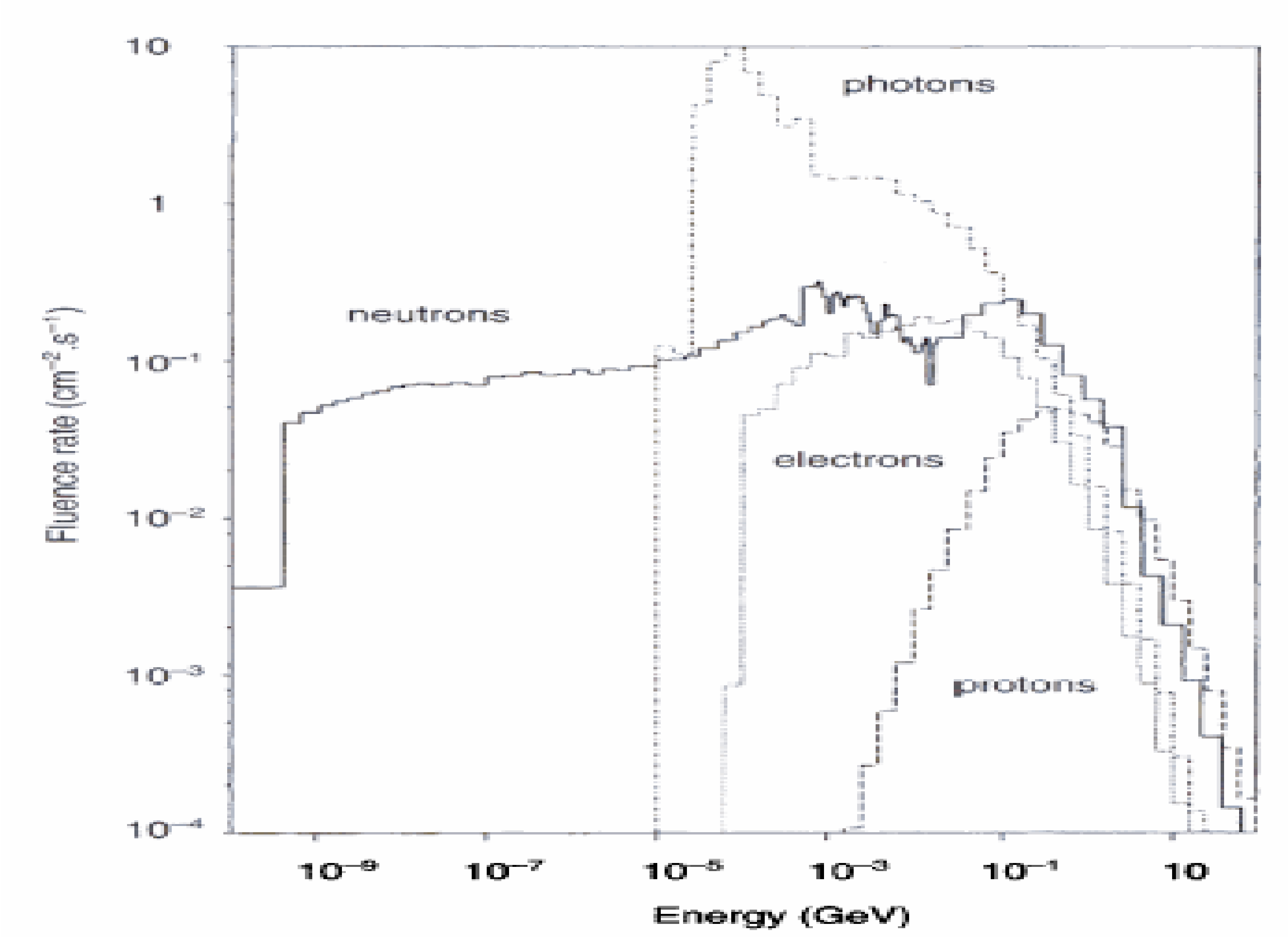
Pressure - altitude relation
10000
1000
100
10
1
Pressure, g.cm-2
0
6
12
18
24
30
Altitude, km
Atmosheric pressure

Onboard Aircraft Dosimetry

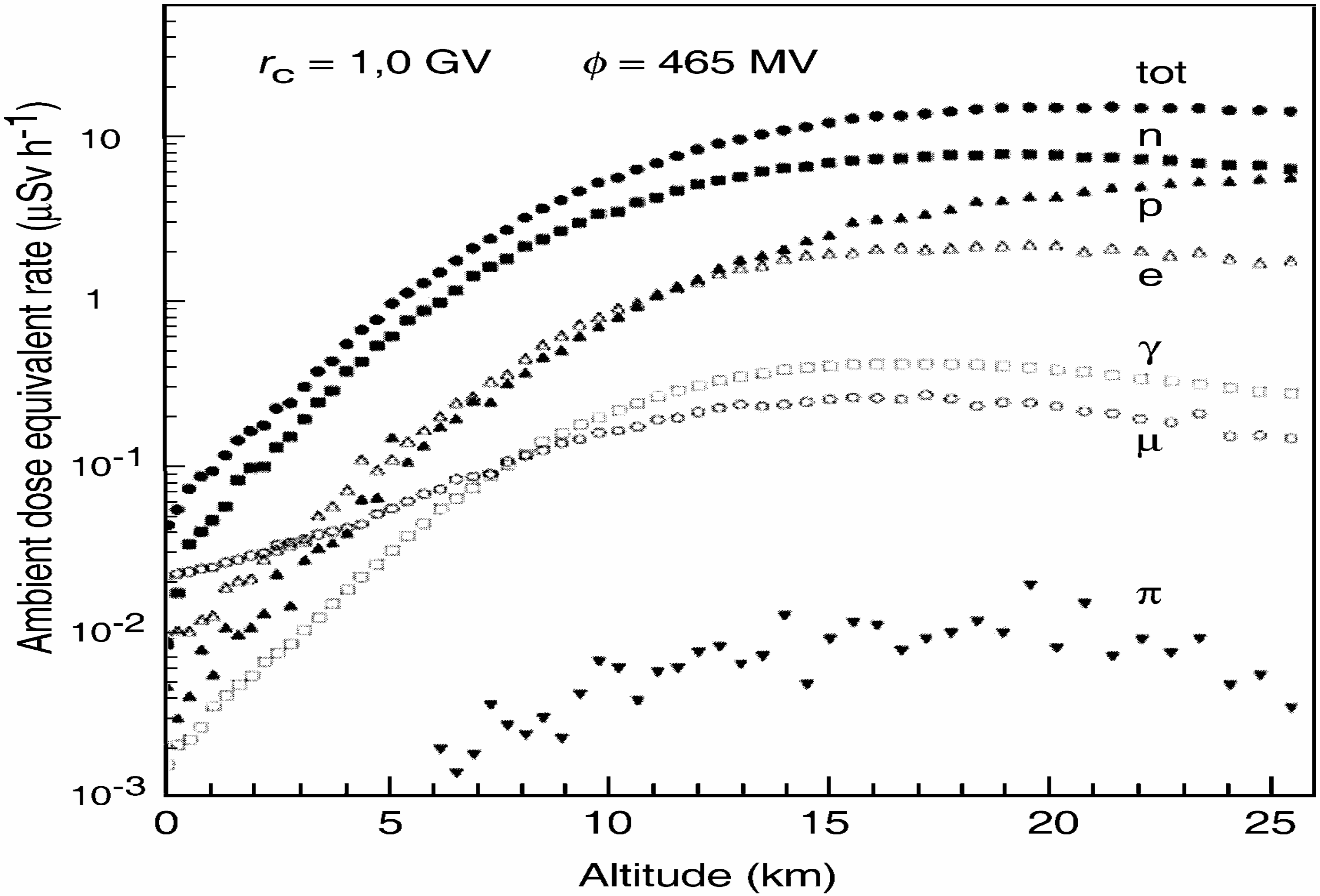
GENERAL

- **Radiation field** – mostly secondary particles created during the passage of primary radiation through 50-70 (supersonic) or 200-250 g.cm^{-2} of atmosphere.
- **Usually divided to components:**
  - Neutrons (two maxima at ~ 1 and ~ 80 MeV) and neutrons-like (high LET); and
  - Non-neutrons (low LET) – electrons, HE protons, mesons photons;
- **Exposure level** - depends only a little on the position in an aircfraft, change with
  - flight altitude;
  - Geomagnetic position; and
  - Solar activity

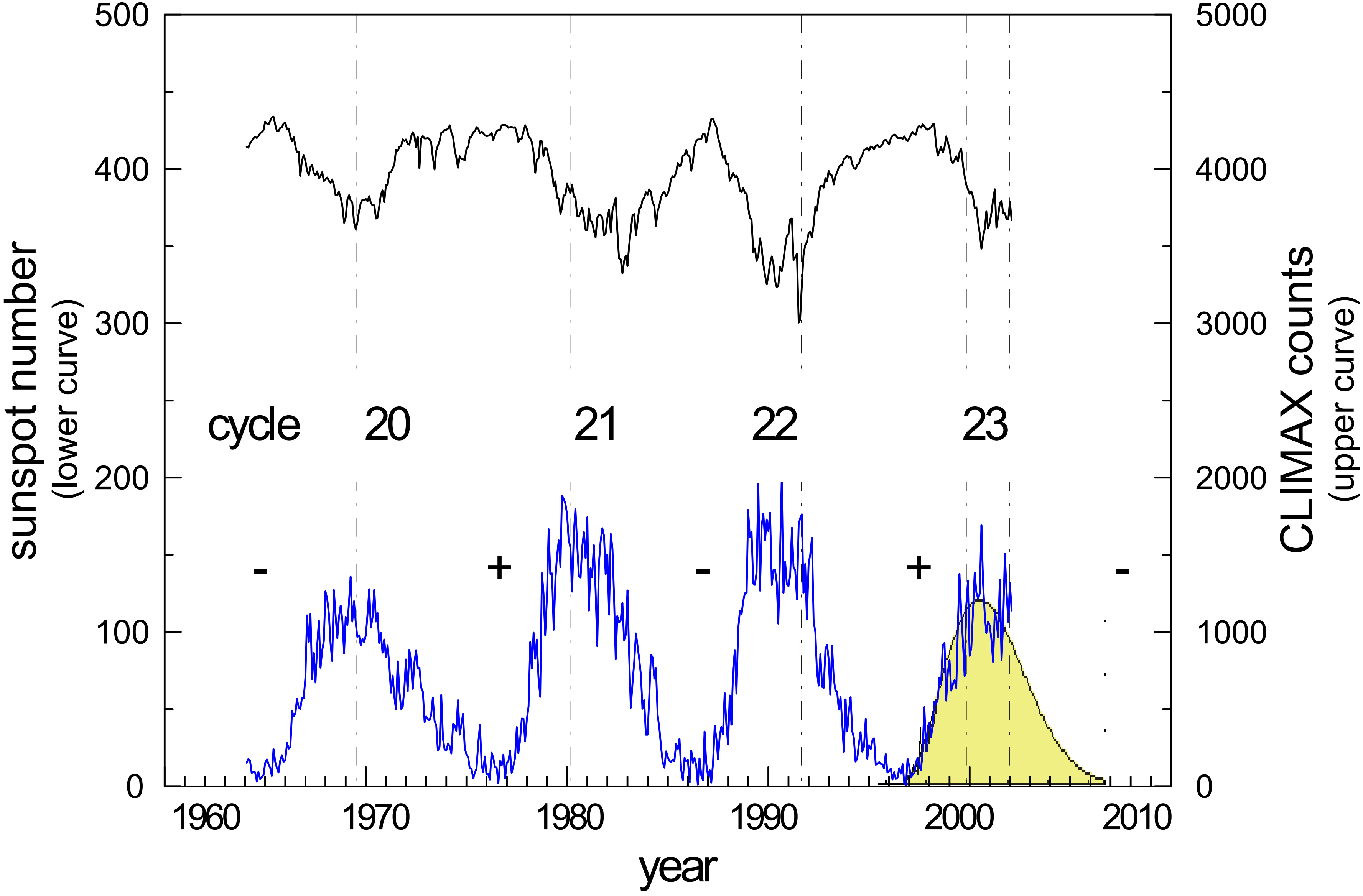
Spectral fluence rate (*EΦE*) of different particles at the depth of 246 g.cm^{-2} a cut-off rigidity of 4 GV-May 1995



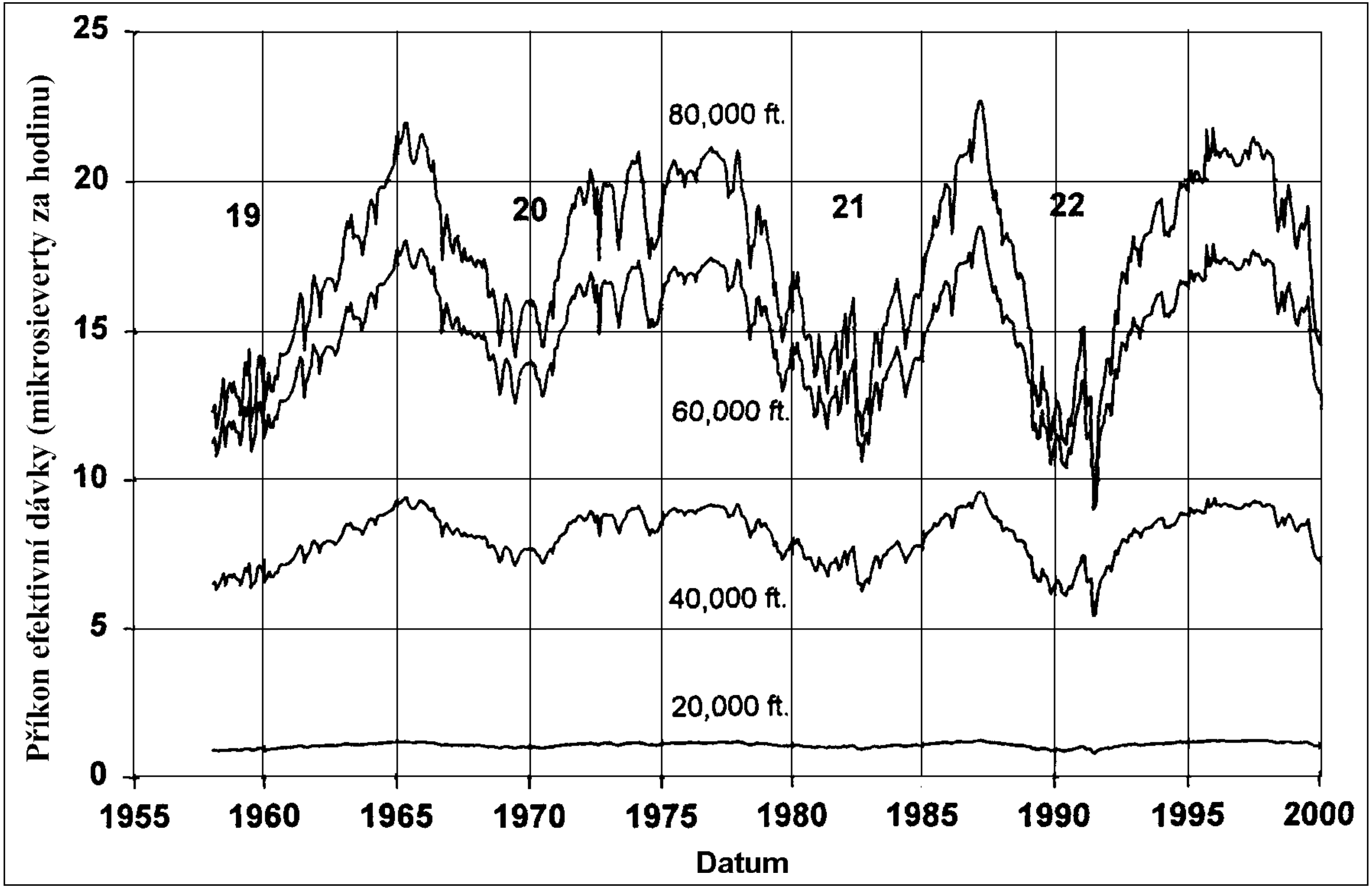
Contribution of different particles to H*(10) rate close to Earth's surface

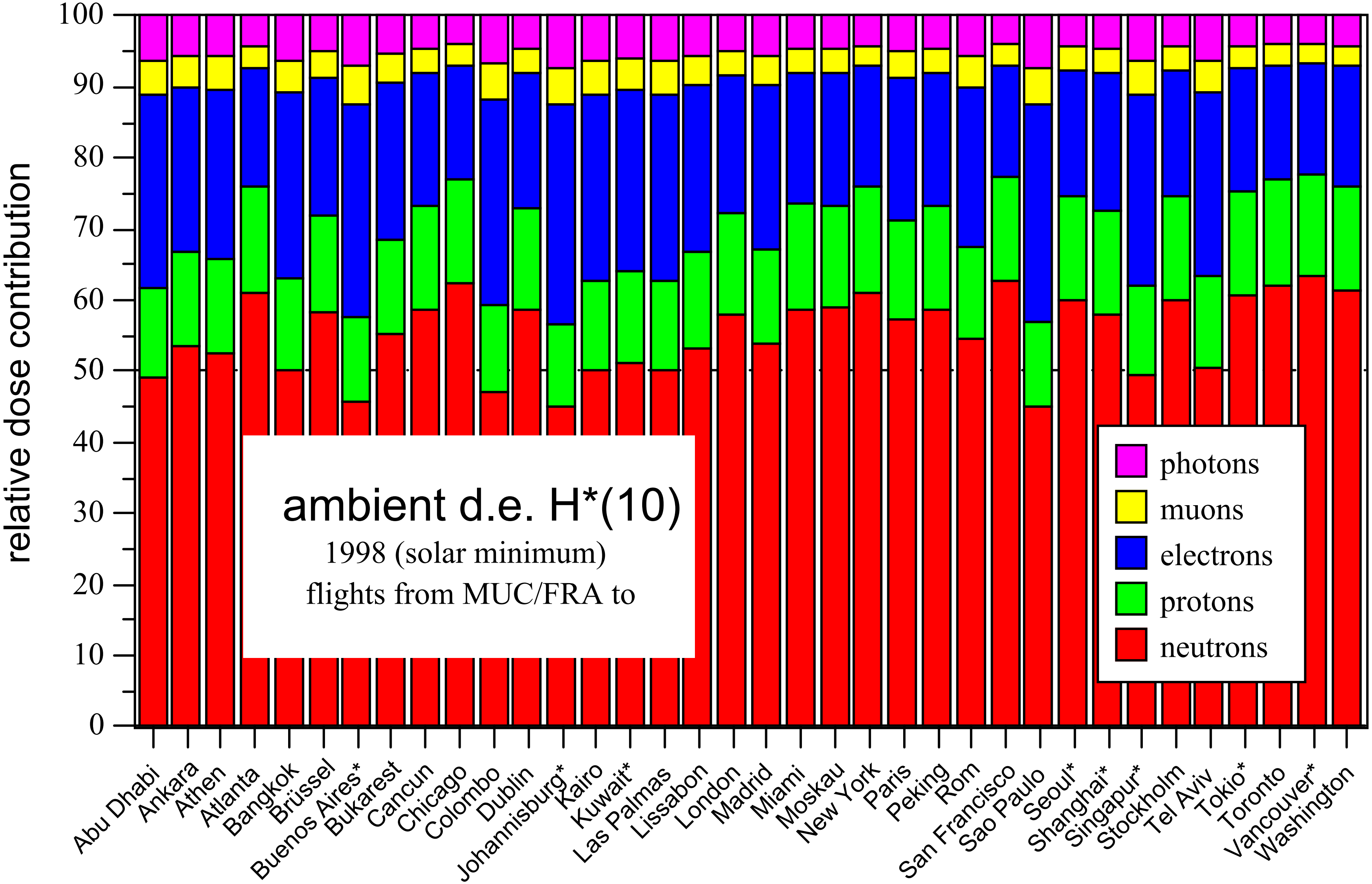


Anti-correlation: solar activity vs. exposure level



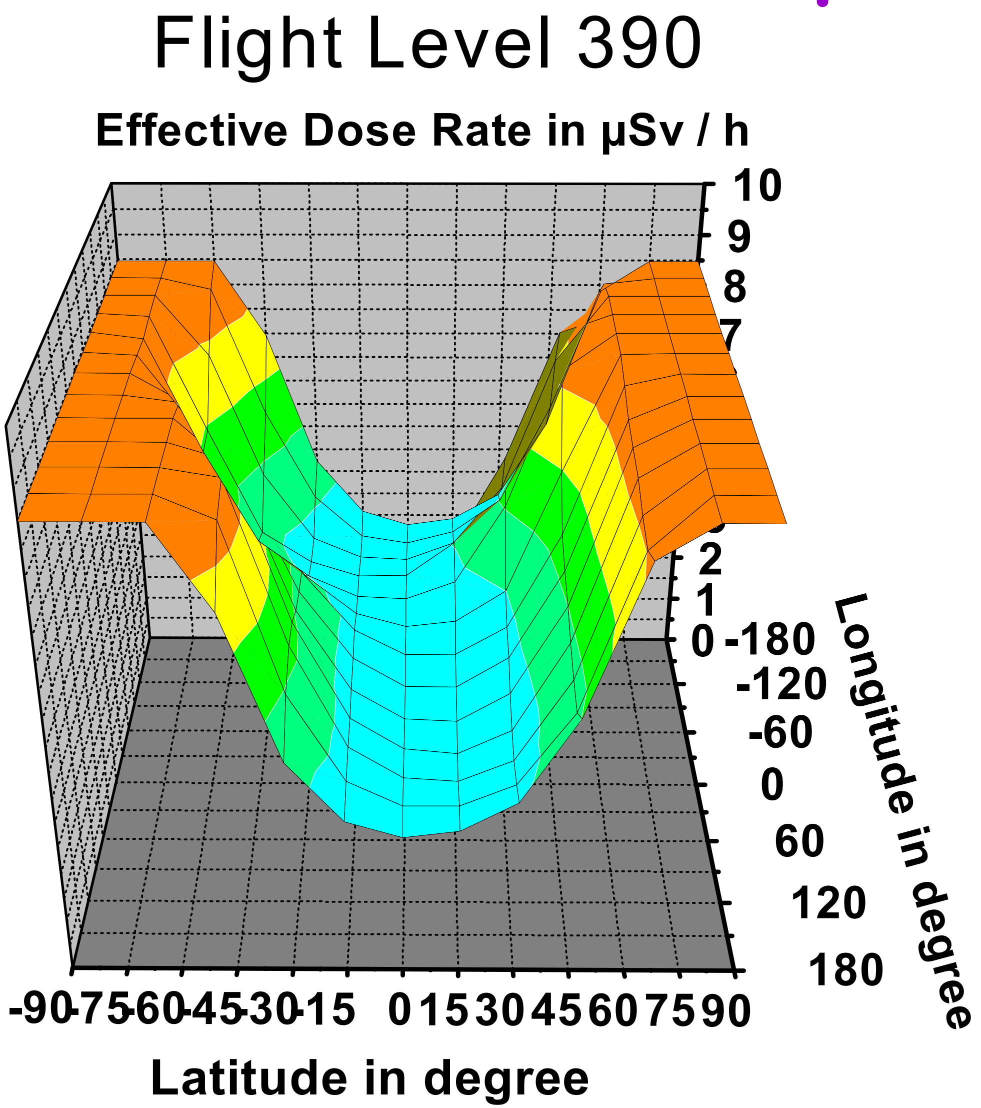
Solar activity influence-altitude effect

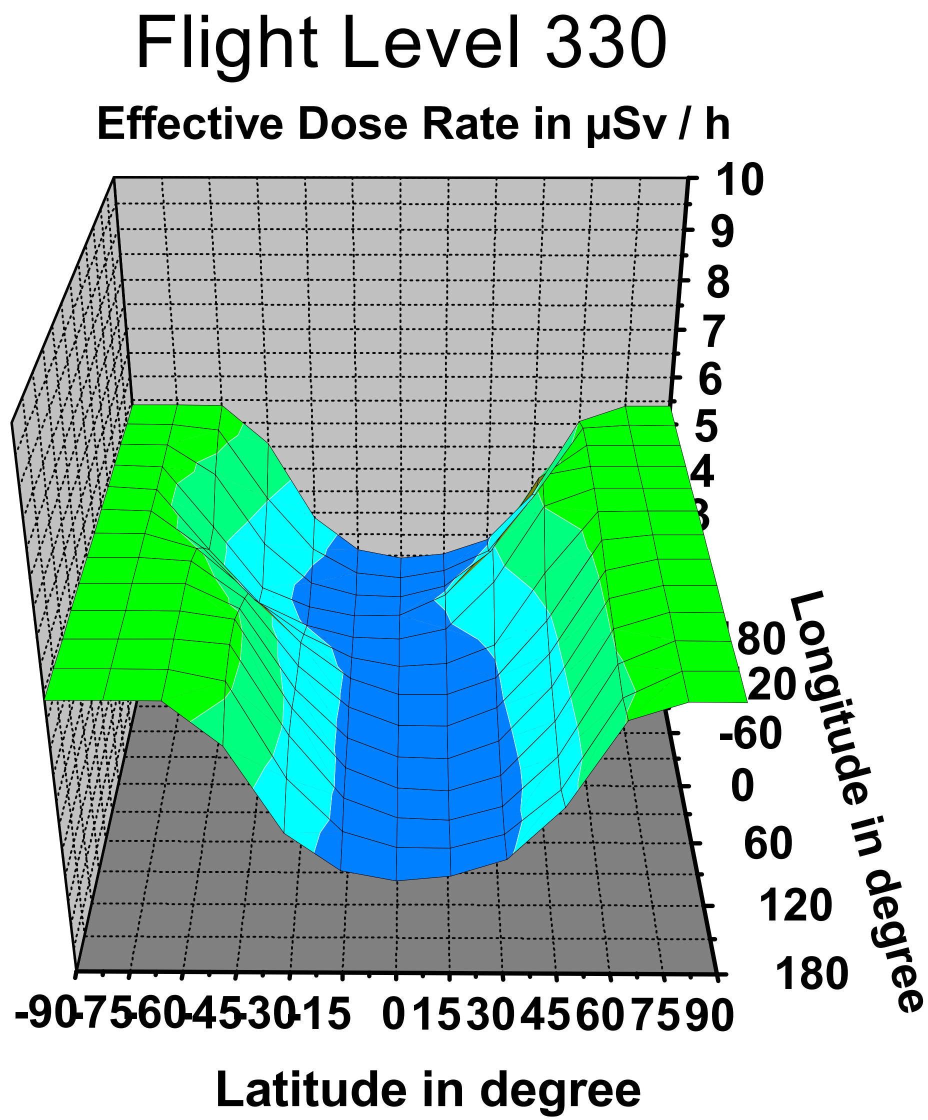


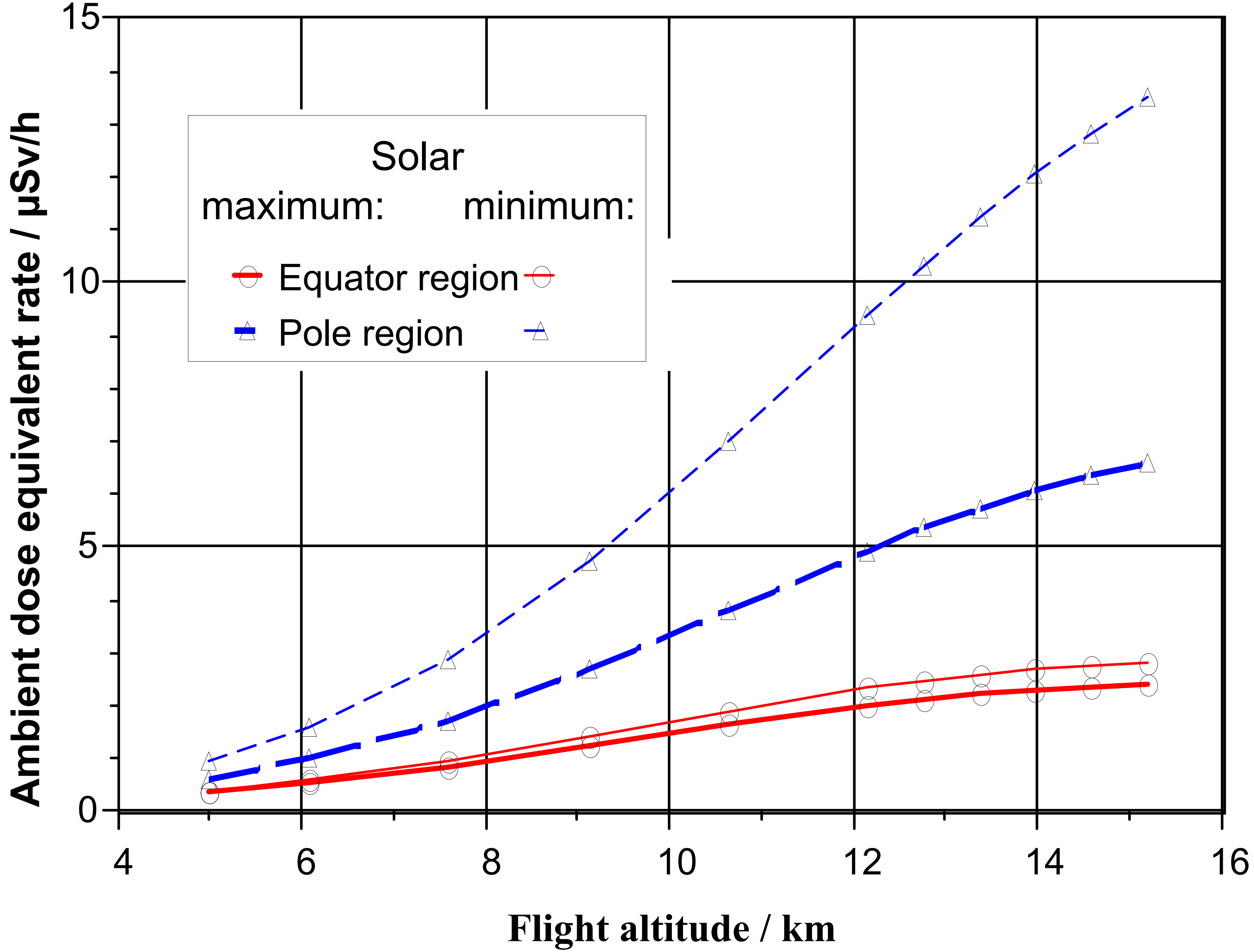


relative dose contribution
100
90
80
70
60
50
40
30
20
10
0
ambient d.e. H*(10)
1998 (solar minimum)
flights from MUC/FRA to
photons
muons
electrons
protons
neutrons
Abu Dhabi
Ankara
Athen
Atlanta
Bangkok
Brüssel
Buenos Aires*
Bukarest
Cancun
Chicago
Colombo
Dublin
Johannisburg*
Kairo
Kuwait*
Las Palmas
Lissabon
London
Madrid
Miami
Moskau
New York
Paris
Peking
Rom
San Francisco
Sao Paulo
Seoul*
Shanghai*
Singapur*
Stockholm
Tel Aviv
Tokio*
Toronto
Vancouver*
Washington

Influence of geo-position and altitude on exposure level



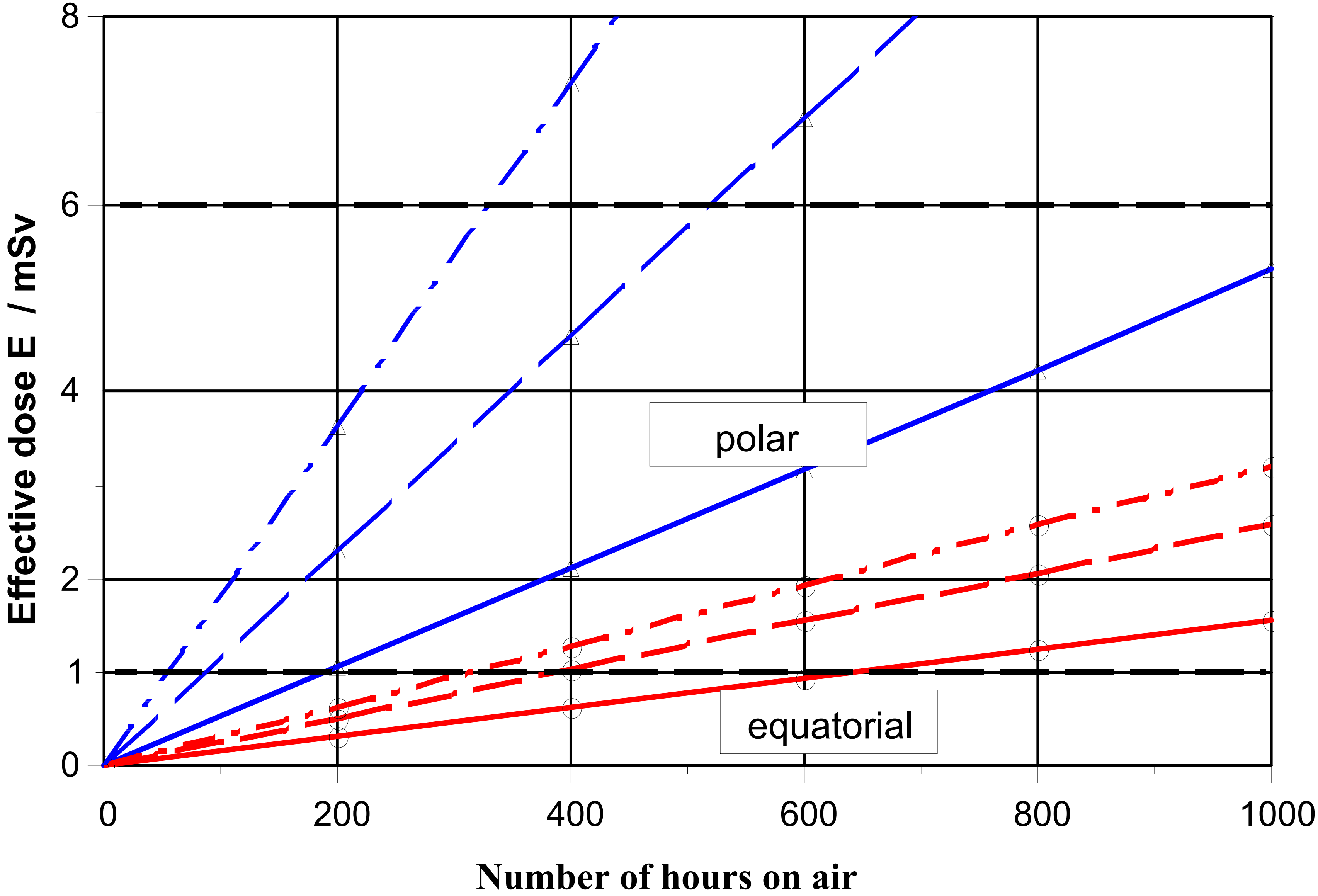




Ambient dose equivalent rate / µSv/h
Flight altitude / km
Solar
maximum:
minimum:
Equator region
Pole region
0
5
10
15
4
6
8
10
12
14
16

Minimum solar activity

Altitudes: 30000ft (—), 40000ft (– –) and 50000ft (– · –)



Dose equivalent excess due to some solar flares (altitude ~ 11 km)

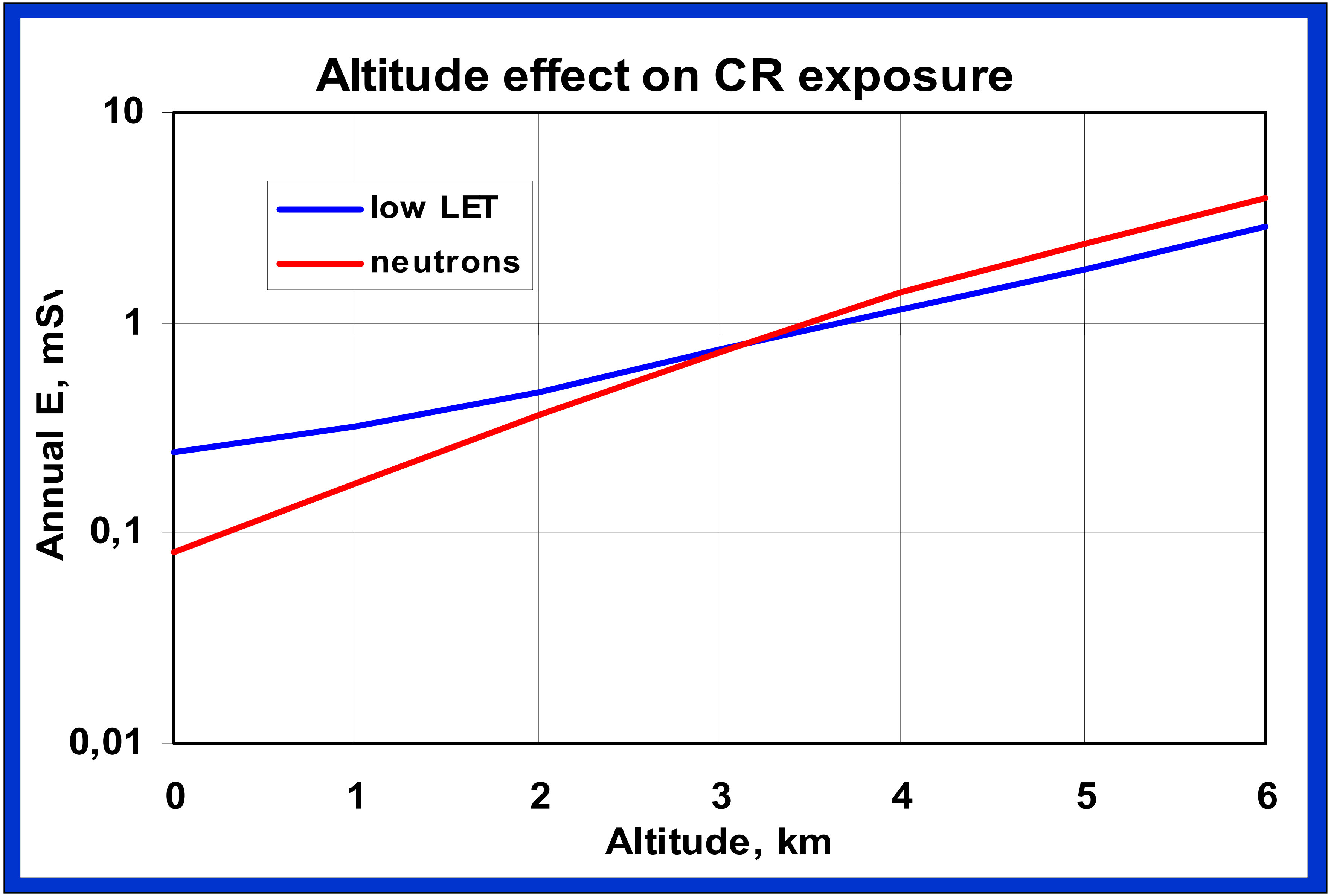
GLE	Date	Route	H_{max} , mSv/h	H_{tot} , mSv
5	23/02/56	LHR-LAX	5 – 8 *)	6 - 9
42	29/09/89		0.27	0.87
60	15/04/01		0.026	0.051
68	21/01/05	south	2.50	0.35
		north	0.30	0.034

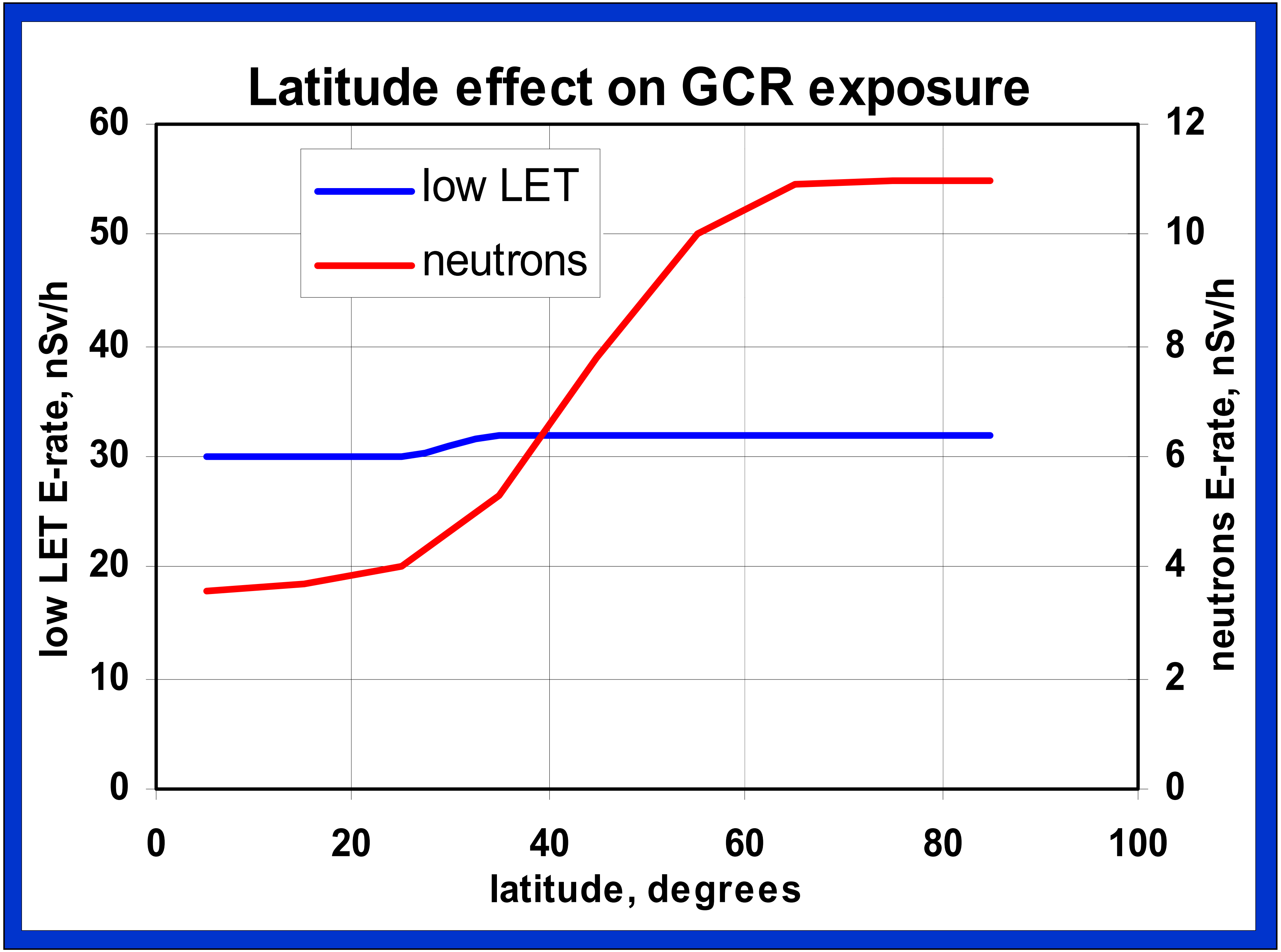
*) Several estimations, within a factor of 10

External exposure from space radiation sources

Radiation fields and doses at the Earth's surface

External exposure close to the Earth's surface due to secondary particles produced by GCR (50ºN)





Latitude effect on GCR exposure
low LET
neutrons
low LET E-rate, nSv/h
neutrons E-rate, nSv/h
latitude, degrees
0
10
20
30
40
50
60
0
2
4
6
8
10
12
0
20
40
60
80
100

Exposure to cosmic rays - UNSCEAR 2000

Population weighted average	E-rate, nSv/h	
	Low LET	Neutrons
Northern hemisphere	31.0	5.6
Southern hemisphere	30.3	4.0
World	30.9	5.5

Conditions	E, μSv		
	low LET	neutrons	total
Outdoors, sea	270	50	320
Qutdoors, altitude adjusted	340	120	460
Shield, occupancy adjusted	280	100	380

Annual E (μSv) due to cosmogenic radionuclides:

^{14}C (12), ^{22}Na (0.15), ^{7}Be (0.03), ^{3}H (0.01)

External exposure from terrestrial radiation

External exposure due to terrestrial radiation

Main sources: **^{238}U, and ^{232}Th series; ^{40}K**

Nuclide	C in soil, Bq/kg		D_{CF}	D_{air} nGy/h	
	Median	Population weighted	nGy/h per Bq/kg	Median	Population weighted
^{40}K	400	420	0.0417	17	18
^{238}U	35	33	0.462	16	15
^{232}Th	30	45	0.604	18	27
Total				51	60

World external exposure rates from terrestrial gamma radiation,

nGy/h	Out- door		In- door		In/ out	
	Aver.	Range	Aver.	Range	Aver.	Range
Median	57	18-93	75	20-200	1.3	0.6-2.3
Population-weighted	59		84		1.4	

Nuclide	$E(Sv)/D_{air}(Gy)$		
	infants	Children	Adults
^{40}K	0.926	0.803	0.709
^{238}U	0.907	0.798	0.695
^{232}Th	0.899	0.766	0.672
Average	0.91	0.79	0.69

Areas of high natural radiation background

Country	Area	Source	Population	D_{air} , nGy/h
Brazil	Guarapari	Monazite sands	73000	90-170 (streets) 90-9000 (beach)
China	Yangjiang	Monazite	80000	370 av.
France	Central	Granitic	$7x10^6$	20-400
India	Kerala	Monazite	100000	200-4000
Italy	Lazio Campana	Volcanic	$5.1x10^6$ $5.6x10^6$	180 av. 200 av.
Switzer	Mountains	divers	300000	100-200

Average external annual effective dose from terrestrial radiation

Indoors:

84 nGy/h x 8760h x 0.8 x 0.7 Sv/Gy =

0.41 mSv

Outdoors:

59 nGy/h x 8760h x 0.2 x 0.7 Sv/Gy =

0.07 mSv

$\sum$ = 0.48 mSv

Radiation dose from natural sources

Source	Worldwide average annual E, mSv	Typical range, mSv
External exposure		
Cosmic rays	0.4	0.3-1.0
Terrestrial radiation	0.5	0.3-0.6
Internal exposure		
Inhalation (Rn!)	1.2	0.2-10
Ingestion	0.3	0.2-0.8
Total	2.4	1-10

Natural radiation in Czech Republic - Review

Altitude – not too high; Many granithic areas; U-mines regions,

Consequences:

- Moderate cosmic ray exposure
- Rather high and extremely variable both external and internal exposure

Outdoors annual exposure to cosmic radiation	E, µSv		
	low LET	neutrons	total
world, sea	270	50	320
World, altitude adjusted	340	120	460
CZ, occupancy adjusted	288	100	388

Nuclide	C in soil, Bq/kg		D_{CF}	D_{air} nGy/h	
	World Median	CZ Median	nGy/h per Bq/kg	World Median	CZ Median
^{40}K	400	613	0.0417	17	25.6
^{238}U	35	44	0.462	16	20.3
^{232}Th	30	41	0.604	18	24.8
Total				51	71

Ranges, Bq/kg:

262-1599 for ^{40}K

18-275 for ^{238}U

18-168 for ^{232}Th

Comparison: World x CZ, in mSv

Type	Average		Range	
	World	CZ	World "typical"	CZ
External	0.9	1.0	0.6 - 1.6	0.64 - 10
Internal	1.5	2.9	0.4 - 10	0.9 - 450
Total	2.4	3.9	1 - 10	1.5 - 460

Regions with elevated levels of background

Own measurements

Example of the variability of annual exposure

Exposure	Source	E, µSv			
		Country house	Indiv. city house	City appartment	City house Basement
Externe	Cosmic Terrestrial	325 1200	325 930	325 960	325 1440
Ingestion	Water only	28	28	28	28
Inhallation	Radon	6600	3200	700	2500-5400
Total		7153	4483	2013	4300-7200

*) Maximum distance 25 km

Further data

- **Annual external exposure inside a city :**

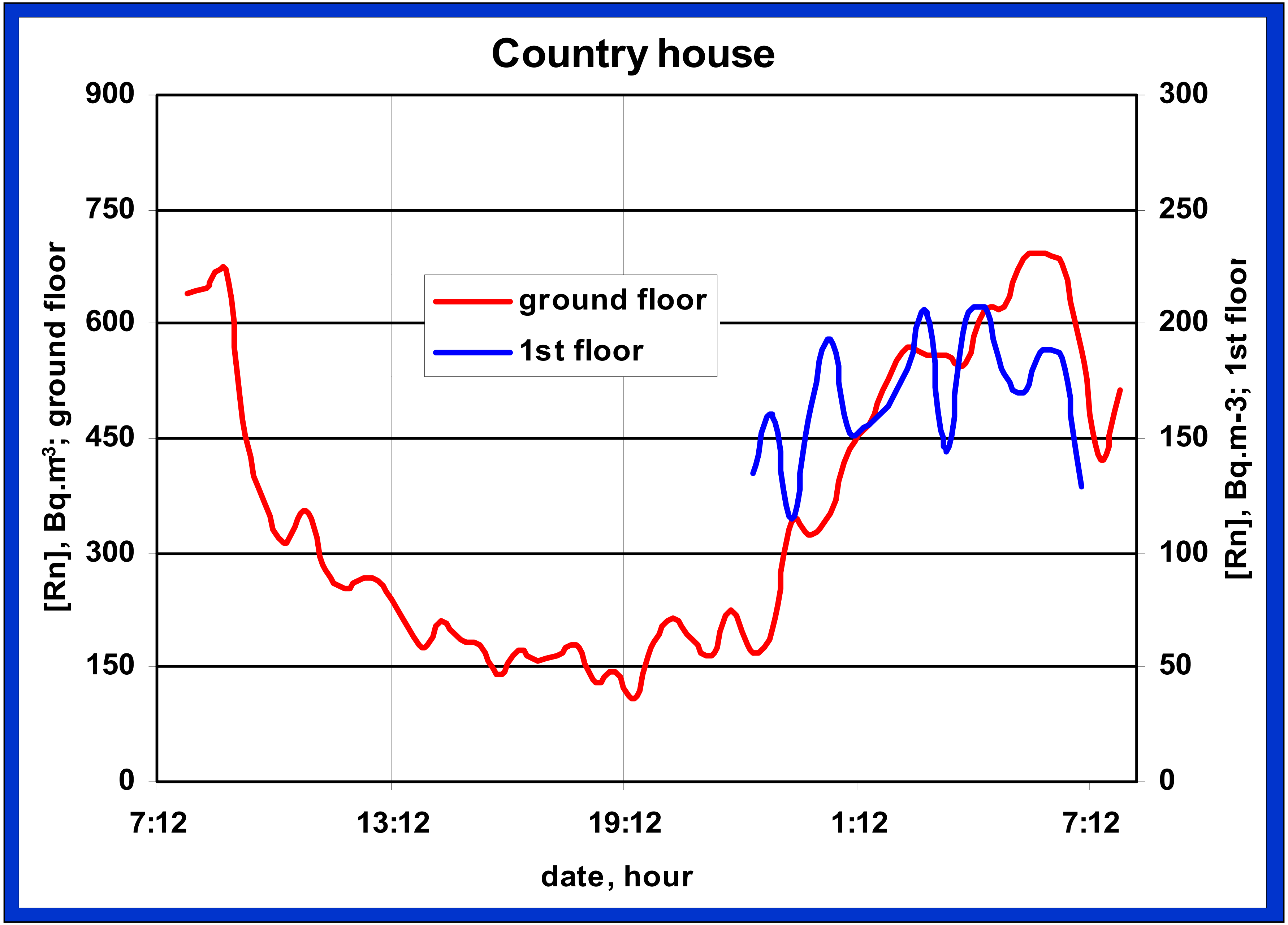
  1.2 – 1.8 mSv

- **Ratio outside/inside a city building:**

  0.75 – 0.95

- **Ratio outside/inside a country house:**

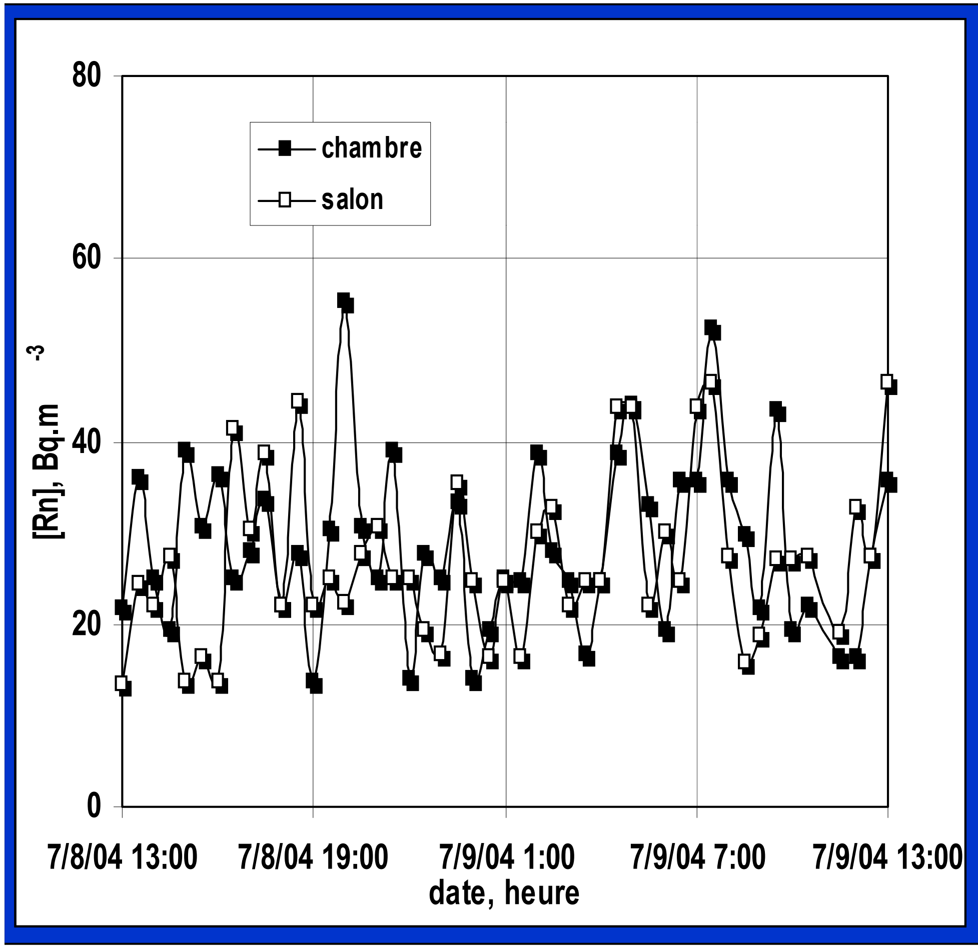
  0.80 – 1.00



Country house
900
750
600
450
300
150
0
300
250
200
150
100
50
0
[Rn], Bq.m³; ground floor
[Rn], Bq.m-3; 1st floor
ground floor
1st floor
7:12
13:12
19:12
1:12
7:12
date, hour

City houses

3rd floor



ground floor