MASTER DI II LIVELLO IN RADIOPROTEZIONE

Raggi cosmici e loro misura

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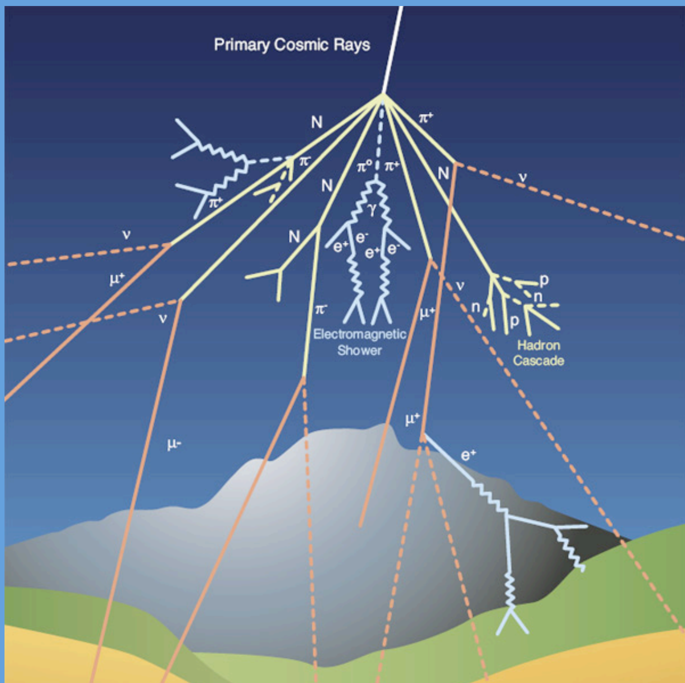
Cosmic rays

The earth is continuously bombarded with high-energy ionizing radiation from outer space. The intensity of the cosmic radiation is partly decreased by the magnetic field associated with the Sun's solar wind and by the Earth's magnetic field.



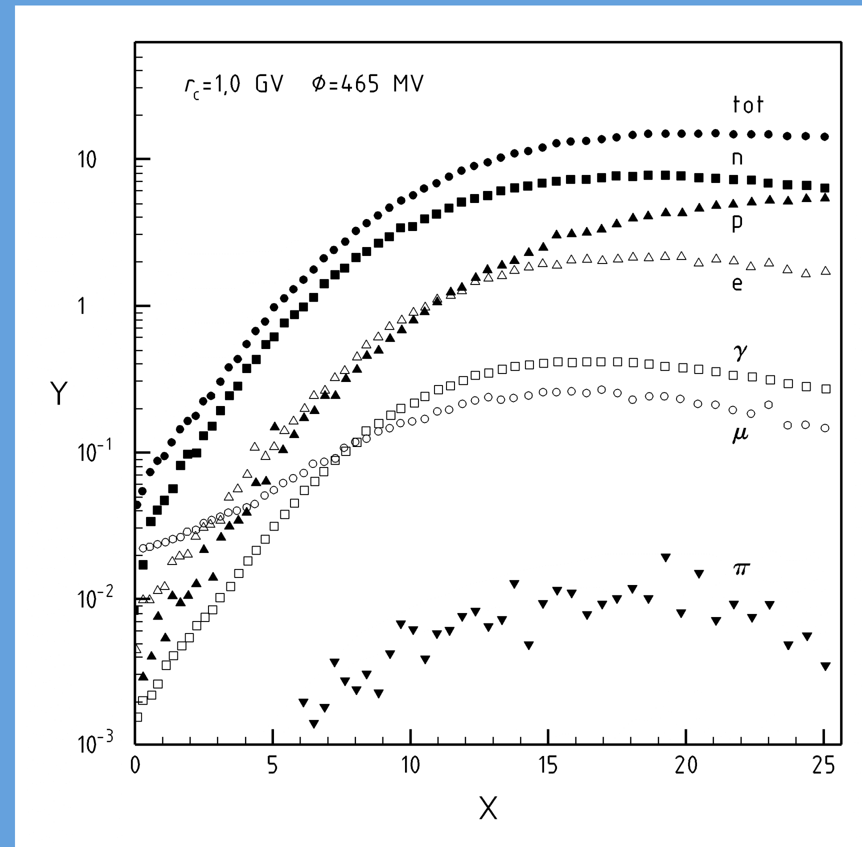
galactic cosmic radiation

protons (~85 %)

helium ions (~12 %)

heavier ions (~1 %)

electrons (~2 %)



Cascade Shower
Schematic representation of particles production in the atmosphere. Shown is a moderately energetic hadronic interaction of primary cosmic ray proton with nucleus of an atmospheric constituent at high altitude that leads small hadrons cascade and electromagnetic cascade

X Altitude (km)
Y Ambient dose equivalent rate (µSv/h)
Conditions: 1 GV cut-off and solar minimum (deceleration potential, ϕ, of 465 MV)

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Space radiation environment

Radiation exposures originate with different type of sources with different properties and variability

Galactic Cosmic Radiation background

Energetic protons and electrons in Van Allen radiation belt

Solar Particles Event sporadic

CGR radiation consists of particles of charge from hydrogen to uranium arriving from outside the heliosphere
Range from 10 MeV/nucleon to 10^{12} MeV/nucleon with fluence rate peak around 300-700 MeV/nucleon

The cyclic variation of solar magnetic field and changes the solar wind velocity cause modulation of CGR spectrum within the heliosphere

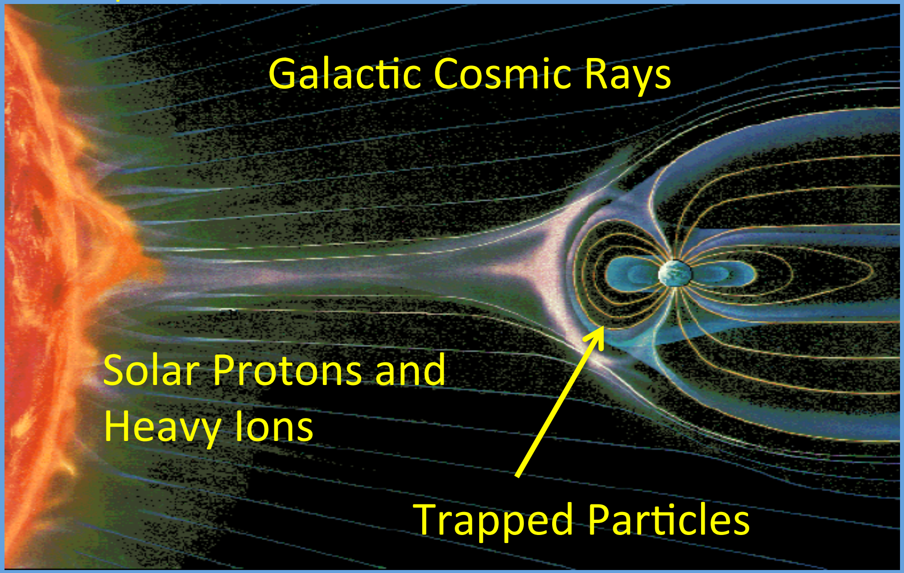

TABLE 3.1—*Relative abundances of nuclei (hydrogen through nickel) at a few representative energies.*

Z	Element	0.2 GeV n^{-1}	1 GeV n^{-1}	5 GeV n^{-1}
1	H	2,200,000 ± 500,000	2,800,000 ± 500,000	4,600,000 ± 700,000
2	He	340,000 ± 80,000	250,000 ± 30,000	230,000 ± 30,000
3	Li	1,000 ± 60	1,400 ± 140	960 ± 100
4	Be	450 ± 50	730 ± 67	680 ± 53
5	B	2,100 ± 90	2,340 ± 102	1,600 ± 69
6	C	8,500 ± 290	7,100 ± 285	6,460 ± 258
7	N	1,940 ± 80	2,000 ± 82	1,610 ± 61
8	0	7,770 ± 280	6,430 ± 243	6,190 ± 217
9	F	183 ± 13	145 ± 11	115 ± 6
10	Ne	1,120 ± 60	1,050 ± 43	960 ± 35
11	Na	273 ± 34	224 ± 12	188 ± 8
12	Mg	1,430 ± 60	1,330 ± 54	1,260 ± 46
13	Al	252 ± 30	229 ± 12	207 ± 9
14	Si[a]	1,000	1,000	1,000
15	P	40 ± 7	47 ± 4	37 ± 2
16	S	164 ± 12	206 ± 11	190 ± 8
17	Cl	36 ± 5	45 ± 4	37 ± 2
18	Ar	63 ± 6	90 ± 7	68 ± 4
19	K	51 ± 6	66 ± 6	51 ± 4
20	Ca	135 ± 10	147 ± 10	119 ± 6
21	Sc	29 ± 5	33 ± 3	22 ± 2
22	Ti	107 ± 9	98 ± 8	74 ± 4
23	V	57 ± 6	44 ± 4	38 ± 3
24	Cr	109 ± 10	98 ± 4	83 ± 5
25	Mn	72 ± 12	55 ± 5	56 ± 4
26	Fe	602 ± 32	607 ± 34	685 ± 37
27	Co	2 ± 1	3 ± 1	4 ± 1
28	Ni	29 ± 4	27 ± 4	36 ± 3

[a]Relative abundances were scaled to silicon which was arbitrarily set equal to 1,000.

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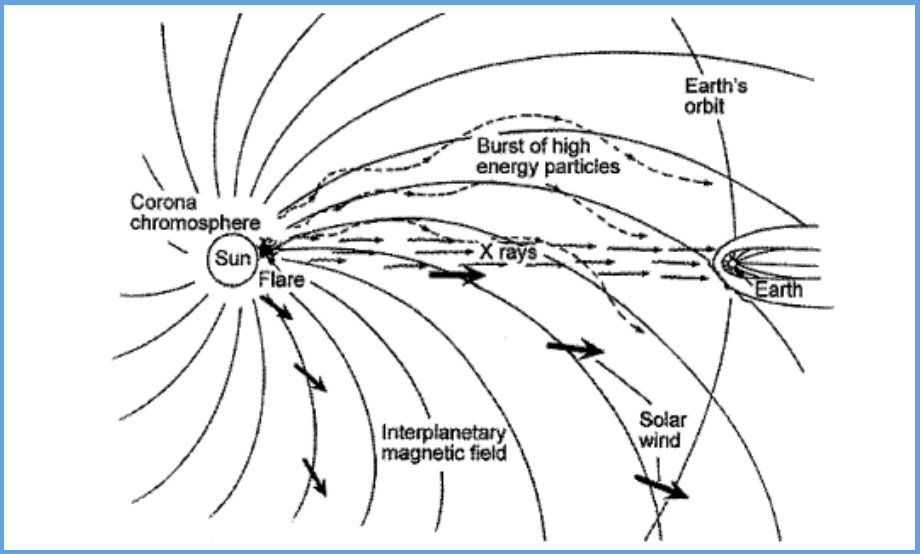
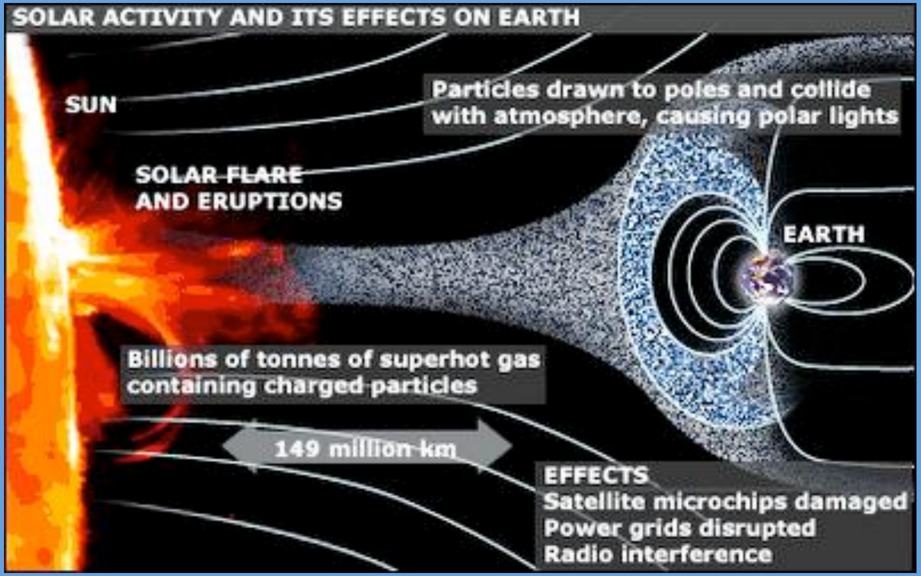
The propagation of solar particles is controlled and organized by the interplanetary magnetic field





Solar Particles Event

Solar flares

A solar flare is a sudden flash of brightness observed over the Sun's surface associated with emission of energy. The flare ejects clouds of electrons, ions, and atoms through the corona of the sun into space.

Interplanetary shock generation (Coronal Mass Ejection)

Massive burst of gas and strong change in solar magnetic field.
The ejected material is a plasma consisting primarily of electron and protons.

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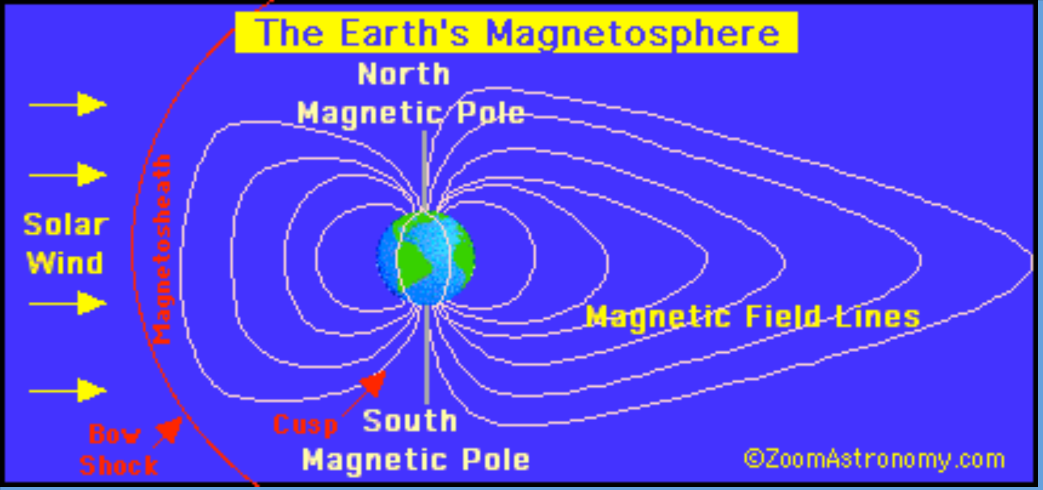

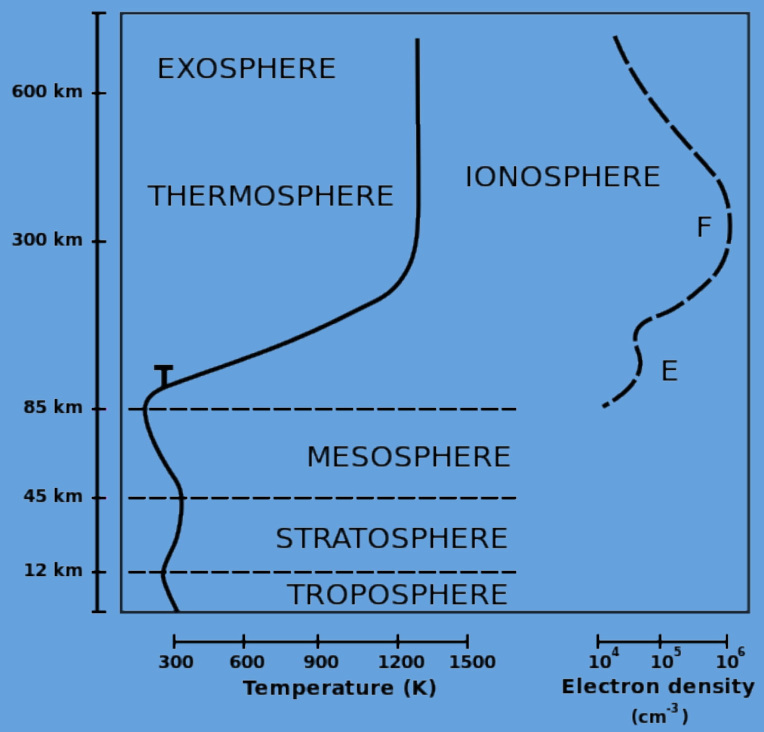

TABLE 3.3—*Average relative element composition of large SPEs normalized to oxygen at 1,000 (adapted from Reames, 1999a).*

Mean Element	*Z*	First Ionization Potential	Solar Photosphere (O ≡ 1,000)	Solar Particle (O ≡ 1,000)
H	1	13.53	1,350,000	1,570,000 ± 220,000
He	2	22.46	132,000 ± 11,000	57,000 ± 3,000
C	6	11.22	479 ± 55	465 ± 9
N	7	14.48	126 ± 20	124 ± 3
O	8	13.55	1,000 ± 161	1,000 ± 10
Ne	10	21.47	162 ± 22	152 ± 4
Na	11	5.12	2.9 ± 0.2	10.4 ± 1.1
Mg	12	7.61	51 ± 6	196 ± 4
Al	13	5.96	4 ± 0.6	15.7 ± 1.6
Si	14	8.12	48 ± 5	152 ± 4
P	15	10.9	0.38 ± 0.04	0.64 ± 0.17
S	16	10.3	2 ± 7	31.7 ± 0.7
Cl	17	12.95	0.4 ± 0.3	0.24 ± 0.1
Ar	18	15.68	4.5 ± 1	3.3 ± 0.2
K	19	4.32	0.18 ± 0.55	0.55 ± 0.15
Ca	20	6.09	3.09 ± 0.14	10.6 ± 0.4
Ti	22	6.81	0.14 ± 0.02	0.34 ± 0.1
Cr	24	6.74	0.63 ± 0.04	2.1 ± 0.3
Fe	26	7.83	42.7 ± 3.9	134 ± 4
Ni	28	7.61	2.4 ± 0.05	6 ± 0.6

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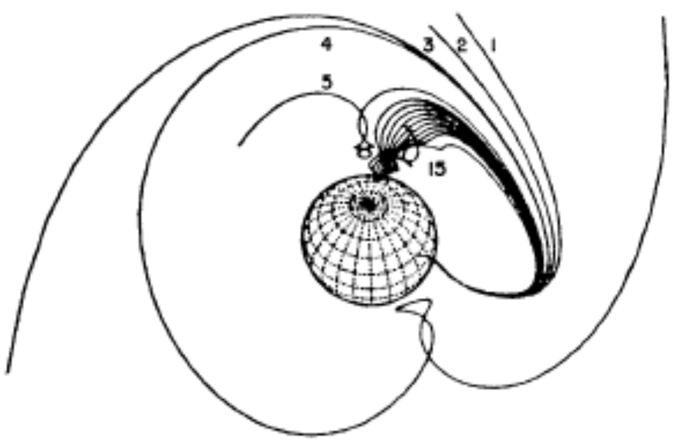
- **A cosmic ray particle has to penetrate the Earth's magnetic field in order to enter the atmosphere.**
- **The quantity which describes the penetrating ability is called magnetic rigidity and is defined as the momentum of the cosmic ray divided by its charge**
- For each point of the magnetosphere and each direction from that point exits a rigidity value below with the cosmic rays are not able to enter the atmosphere. This rigidity is called geomagnetic cut-off
- Value of cut-off is much lover near the poles than in equatorial region. This means that only high energy particles can reach the atmosphere in the equatorial region



magnetic rigidity

P = p /Ze

momentum per charge (of a particle in a magnetic field)

NOTE 1 The unit of magnetic rigidity is kg m s^{-2} A^{-1}=Tm = $Vm^{-1}s$.
T (tesla) is the magnetic flux density

A frequently used unit is V (or GV) in a system of units where the values of the speed of light, c, and the charge on the proton, e, are both 1, and the magnetic rigidity is given by *pc/Ze*.

NOTE 2 Magnetic rigidity characterizes charged particle trajectories in magnetic fields. All particles having the same magnetic rigidity will have identical trajectories in a magnetic field, independent of particle mass or charge.

geomagnetic cut-off rigidity

*P*c

the minimum magnetic rigidity an incident particle can have and still penetrate the geomagnetic field to reach a given location above the Earth.

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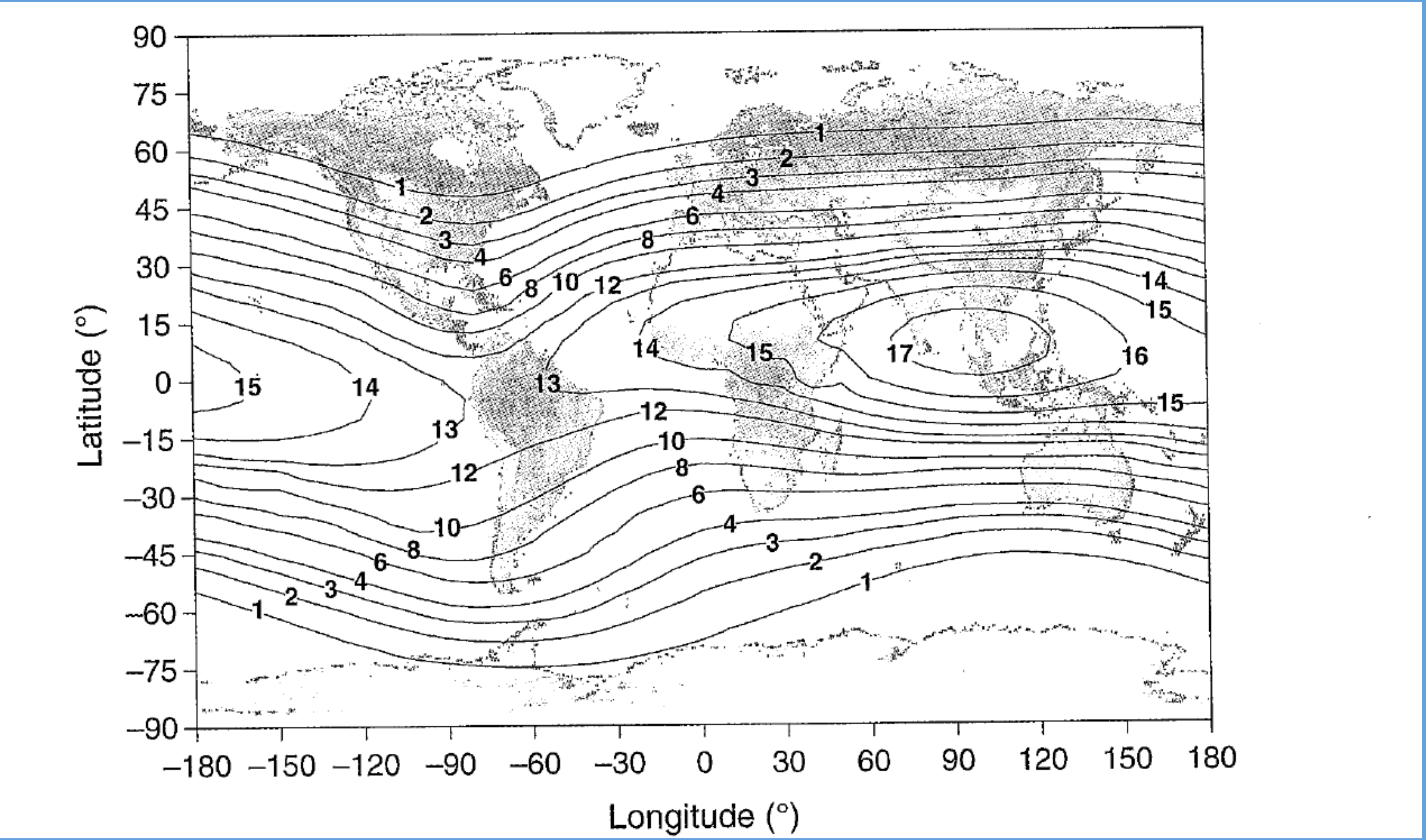

Vertical cut-off rigidity In GV based on data in 1990 at 20 km (Shea and Smart 2011)

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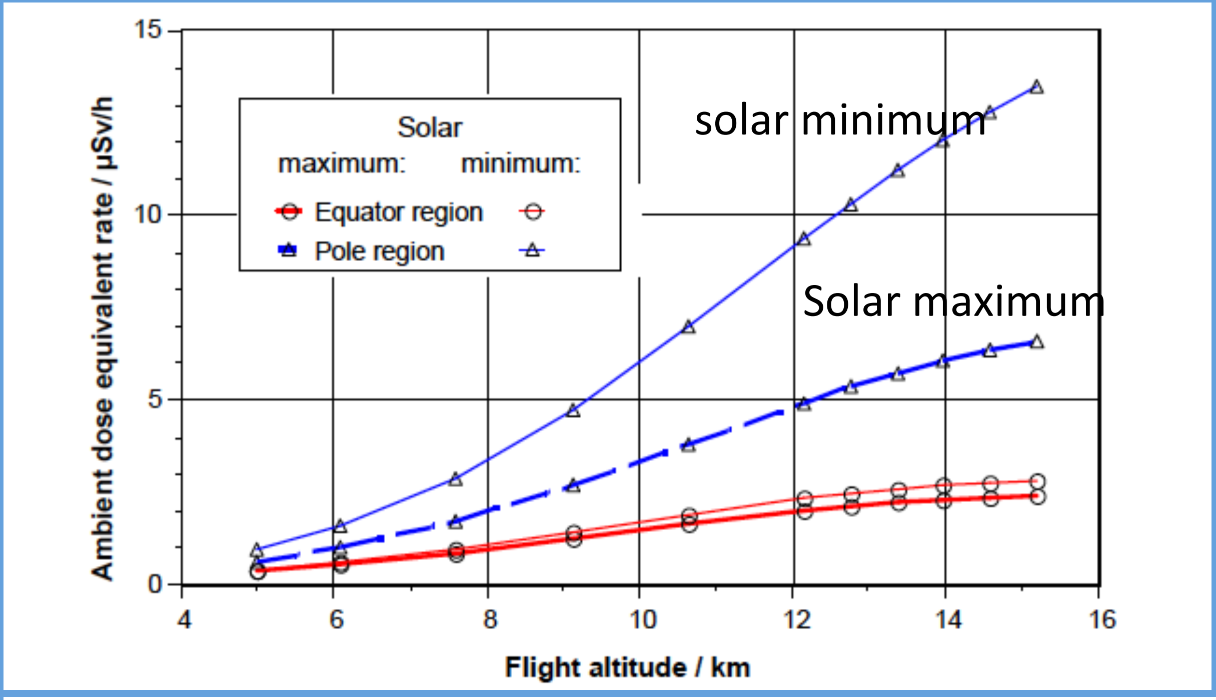
The cosmic radiation field (in the Earth´s atmosphere), to which aircraft crew members are exposed, has two different origins:

- from the universe in general the so-called galactic cosmic radiation)
- from the Sun the so called solar cosmic radiation.



Calculated ambient dose equivalent rate, d$H^*(10)$/dt, for conditions close to solar maximum activity (Jan.1990) and close to solar minimum (Jan. 1998), both at zero-meridian (λ=0°) and geographic latitude ϕ of 0° (red lines) resp. 90°(blue lines).(For uncertainties in calculated values see CH.IV.6 and Ch.V.5)

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- Galactic energetic charged particles (galactic cosmic radiation (GCR)) are mostly protons (~85 %) and helium ions (~12 %), the rest includes nuclei of all known elements and some electrons. Their energy extends up to about 10^{20} eV.

- The GCR interacts with the atmosphere producing secondary radiation, which together with the primary incident particles give rise to radiation exposure throughout the atmosphere decreasing in intensity with depth from the altitude of supersonic aircraft down to sea level.

- **The dose from GCR varies not only with altitude but also with the geomagnetic coordinates (longitude and latitude) being larger towards the poles and smaller near the equator. It also depends on the solar activity, which varies according to a cycle about 11 years long.**

- **The GCR contribution to the aircraft crew exposure is about 95 %.**

- **GCR exposure is fairly stable and predictable.**

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- Solar energetic charged particles can contribute to the aircraft crew exposure through occasional so-called solar particle events (SPE's). These are produced by sudden, sporadic releases of energy in the solar atmosphere (solar flares), and by coronal mass ejections (CMEs).
- During such events a large number of mainly high-energy protons is produced and an increased fluence of particles at aviation altitudes may be observed.
- Only a small fraction of the SPEs, on average one per year, causes an increased dose rate at aviation altitudes.
- Those events can be observed with neutron monitors at ground level: ground level events (GLEs).

- The largest events often take place on either side of the period of maximum solar activity as measured by sunspot number. Any rise in dose rate associated with an event is quite rapid, usually taking place in minutes. The duration may be hours to several days.
- The prediction of which events will give rise to significant increases in dose rate at aircraft altitudes is not currently possible.
- Estimation of the doses to aircraft crew in the event of a GLE must be made retrospectively. Principally it is possible due to the existence of a number of geo-magnetically dispersed, ground level neutron monitors, and because the observed neutron fluence at ground level is primarily caused by the cosmic radiation.

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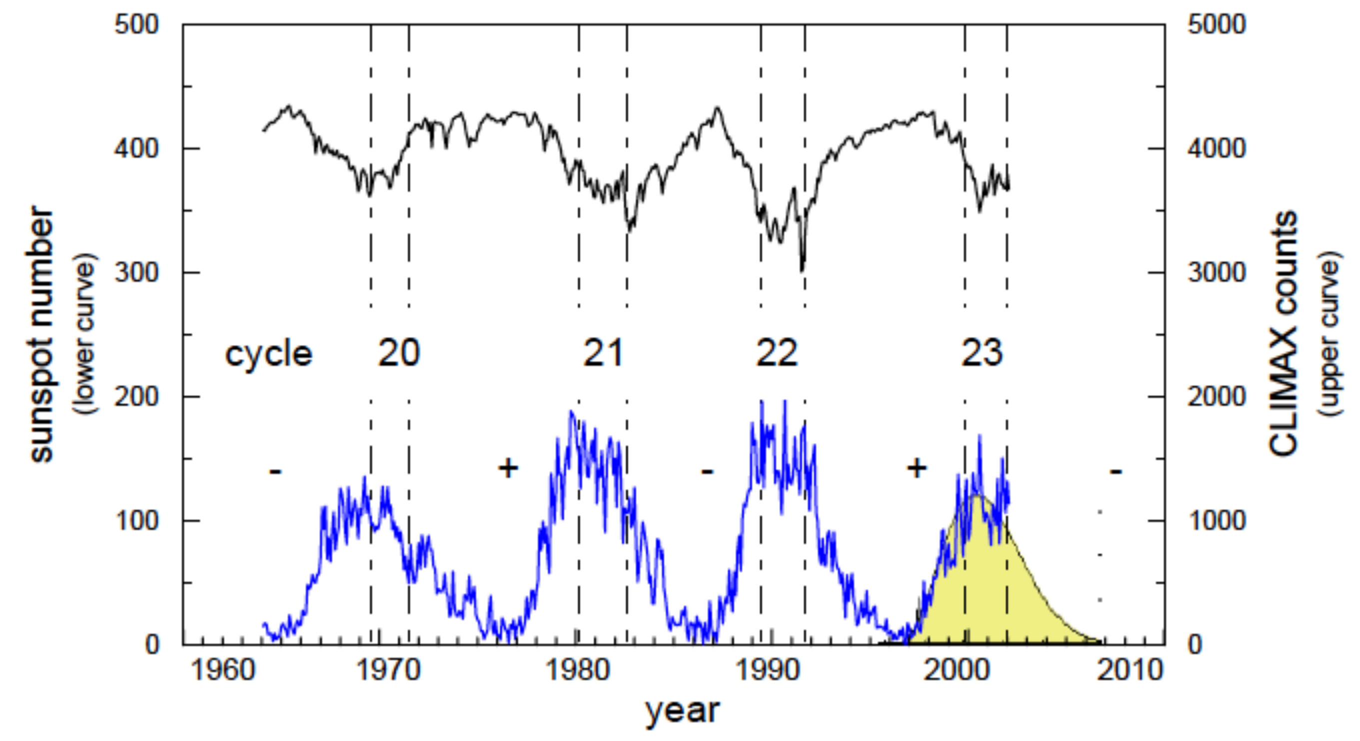

Figure shows how the neutron monitor count rate has varied with the number of sunspot during the time period from1960 to the present.

The sunspot number reflects the activity of the sun and a smoothed curve is used to identify the maxima and minima of the sun activity.

The neutron fluence sometimes also decreases as an effect of increased solar wind and the increases in associated magnetic field.

Those effects decrease the intensity of the GCR at the top of the atmosphere.
Such events are called "Forbush decreases", they may occur a handful of times each year They may last for several days

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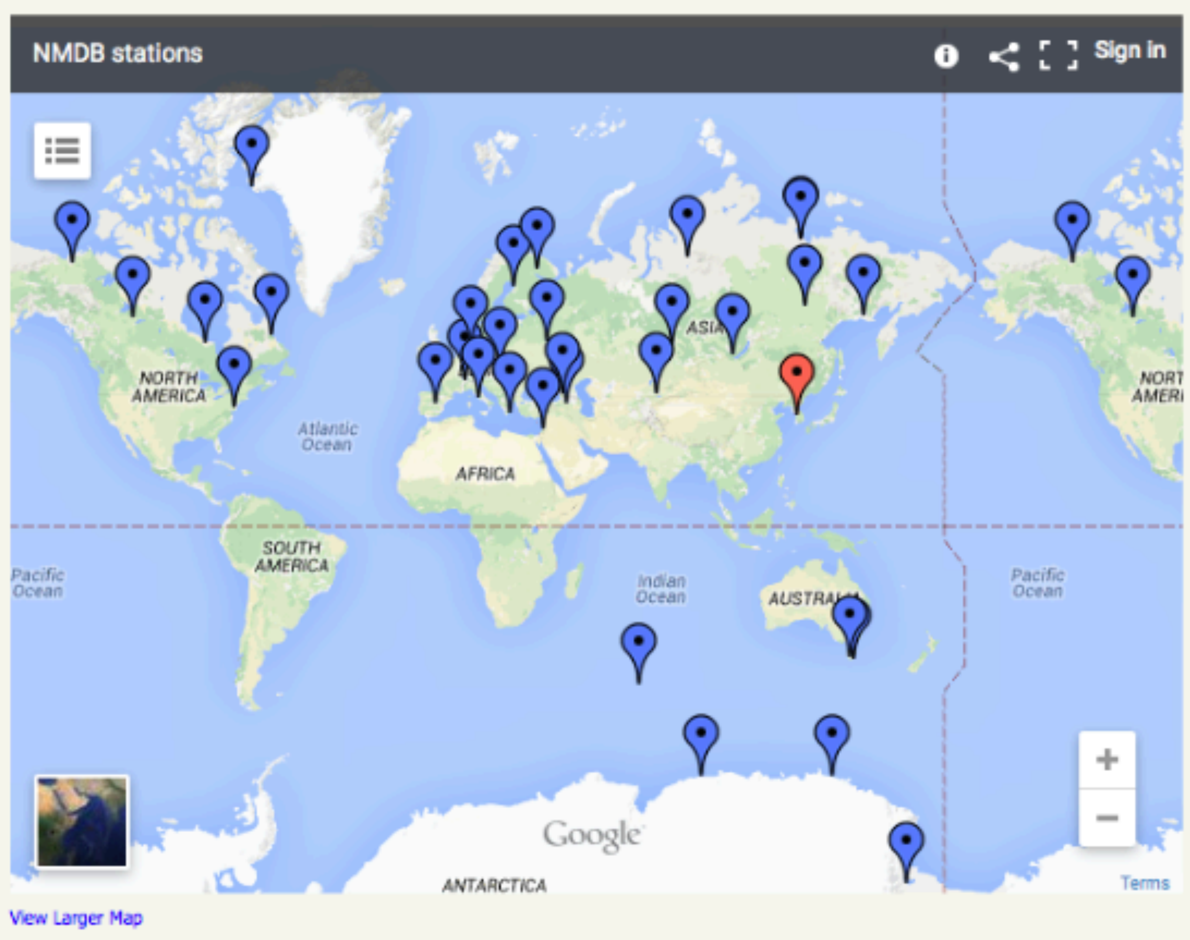

The cosmic ray station of Rome joined the worldwide network of neutron monitors with the purpose to study the time variations of primary cosmic rays (Studio Variazioni Intensità Raggi Cosmici: S.V.I.R.CO.) and their modulation in the heliosphere. From July 1957 to April 1997, the SVIRCO Station (now Observatory) performed uninterrupted measurements at the Physics Department “G. Marconi” of “La Sapienza” University of Rome (41.90° N, 12.52° E, altitude about 60 m asl). In May 1997 the neutron monitor was moved into the Physics Department “E. Amaldi” of “Roma Tre” University. Since then SVIRCO Observatory (INAF/IFSI-UNIRomaTre collaboration) has been continuously operating at the new location (41.86° N, 12.47° E, about sea level).

Specifications:
Detector 20-NM64 (three 3-counter, one 5-counter and one 6-counter units)
Geographic latitude 41.86° N Geographic longitude 12.47° E Altitude Sea level
Effective vertical cutoff rigidity (Epoch1995) 6.27 GV

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Some of the codes are based on Monte Carlo simulations of the radiation field (AVIDOS, EPCARD, JISCARD EX, PANDOCA, PLANETOCOSMICS(Bern code), and QARM). The SIEVERT code uses a worldwide grid of dose rates calculated with EPCARD. Two codes (CARI, FREE) use an analytic calculation of particle transport through the atmosphere based on LUIN99/LUIN2000 and PLOTINUS calculations, respectively. Other codes are based on measurements only (FDOScalc, PCAIRE) and some use the E/H*(10) conversion as calculated by the MonteCarlo codes mentioned above.

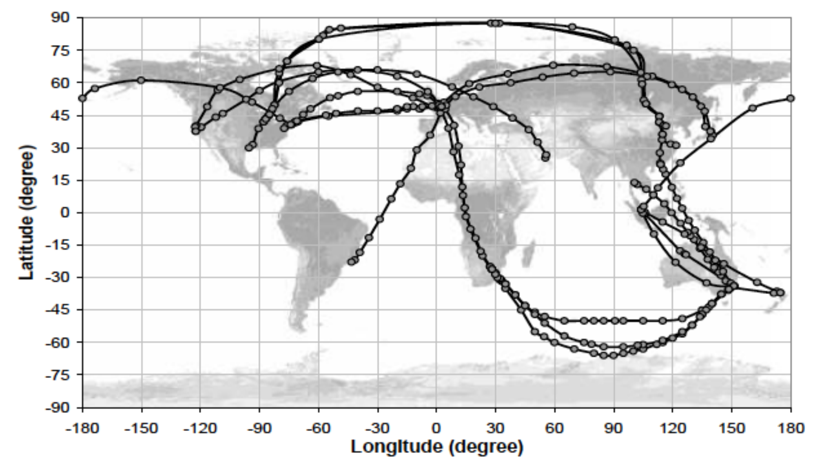

Table 2.4. Computer codes for calculation of the radiation exposure of aircraft crew due to galactic cosmic radiation. For detailed description and references see sections 2.3.1 to 2.3.11.

Computer Code	Method based on	Reference	Primary galactic cosmic radiation spectra (if applied)	Cut off rigidity	Dose conversion
AVIDOS 1.0	FLUKA Monte Carlo code calculations	(Beck, 2007; Roesler, 2002)	Gaisser *et al* modified by balloon measurements (Gaisser, 2001; Beck, 2007)	Vertical cut off rigidity (Smart, 1997)	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000)
CARI-6M	LUIN99/LUIN2000 code calculations	(Friedberg, 1992)	below 10 GeV (Garcia-Munoz, 1975), above10 GeV (Peters, 1958) normalized to 10.6 GeV (Gaisser, 1998)	Vertical cut-off rigidity (Shea, 2000) non-vertical cut-off rigidities (Heinrich, 1979)	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000)
EPCARD.Net 5.4.1	FLUKA Monte Carlo code calculations	(Mares, 2009; Roesler,2002)	(Badhwar, 2000)	Vertical cut-off rigidity (Bütikofer, 2007)	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000; Mares, 2007)
FDOScalc 2.0	Experimental data (97-99; 03-06)	(Schrewe, 2000; Wissmann, 2006; Wissmann, 2010)	Not applied	Vertical cut-off rigidity MAGNETOCOSMICS (Desorgher, 2006)	
IASON-FREE 1.3.0	PLOTINUS code calculations	(Felsberger, 2009)	below 10 GeV (Garcia-Munoz, 1975), above10 GeV (Peters, 1958) normalized to 10.6 GeV (Gaisser, 1998)	Vertical cut-off rigidity (Shea, 2000) non-vertical cut-off rigidities (Heinrich, 1979)	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000)
JISCARD EX	PHITS Monte Carlo code calculations	(Yasuda, 2008a; Yasuda, 2008b)	(Nymmik, 1992)	Vertical cut-off rigidity pre-calculated with MAGNETOCOSMICS (Desorgher, 2006)	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000)
PANDOCA	PLANETOCOSMICS 2.0; GEANT4.9.1 Monte Carlo code calculations	(http://corsray.unibe.ch) (http://geant4.web.cern.ch/geant4/)	(Gleeson, 1968) (Usoskin, 2005)	Vertical cut-off rigidity, pre-calculated with PLANETOCOSMICS 2.0	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000)
PCAIRE	Experimental data (since 97)	(Lewis, 2001; Lewis, 2002; Lewis, 2004; Takada, 2007)	Not applied	Vertical cut-off rigidity (Lewis, 2002)	ICRP 60 (ICRP, 1990)
PLANETOCOSMICS 2.0	GEANT4 Monte Carlo code calculations	(http://corsray.unibe.ch)	(Gleeson, 1968; Garcia-Munoz, 1975)	Vertical cut-off rigidity (Bütikofer, 2007)	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000)
QARM 1.0	MCNPX Monte Carlo code calculation	(Lei, 2004; Lei, 2006; Dyer, 2007; http://mcnpx.lanl.gov)	(Badhwar, 2000)	Vertical cut-off rigidity (Smart, 1997)	ICRP 74 (ICRP, 1996), (Pelliccioni, 2000)
SIEVERT 1.0	EPCARD version3.3.4 code calculations	(http://sievert-system.org; Bottollier-Depois, 2007)	(Badhwar, 2000)	Vertical cut-off rigidity (Smart, 1997)	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000)

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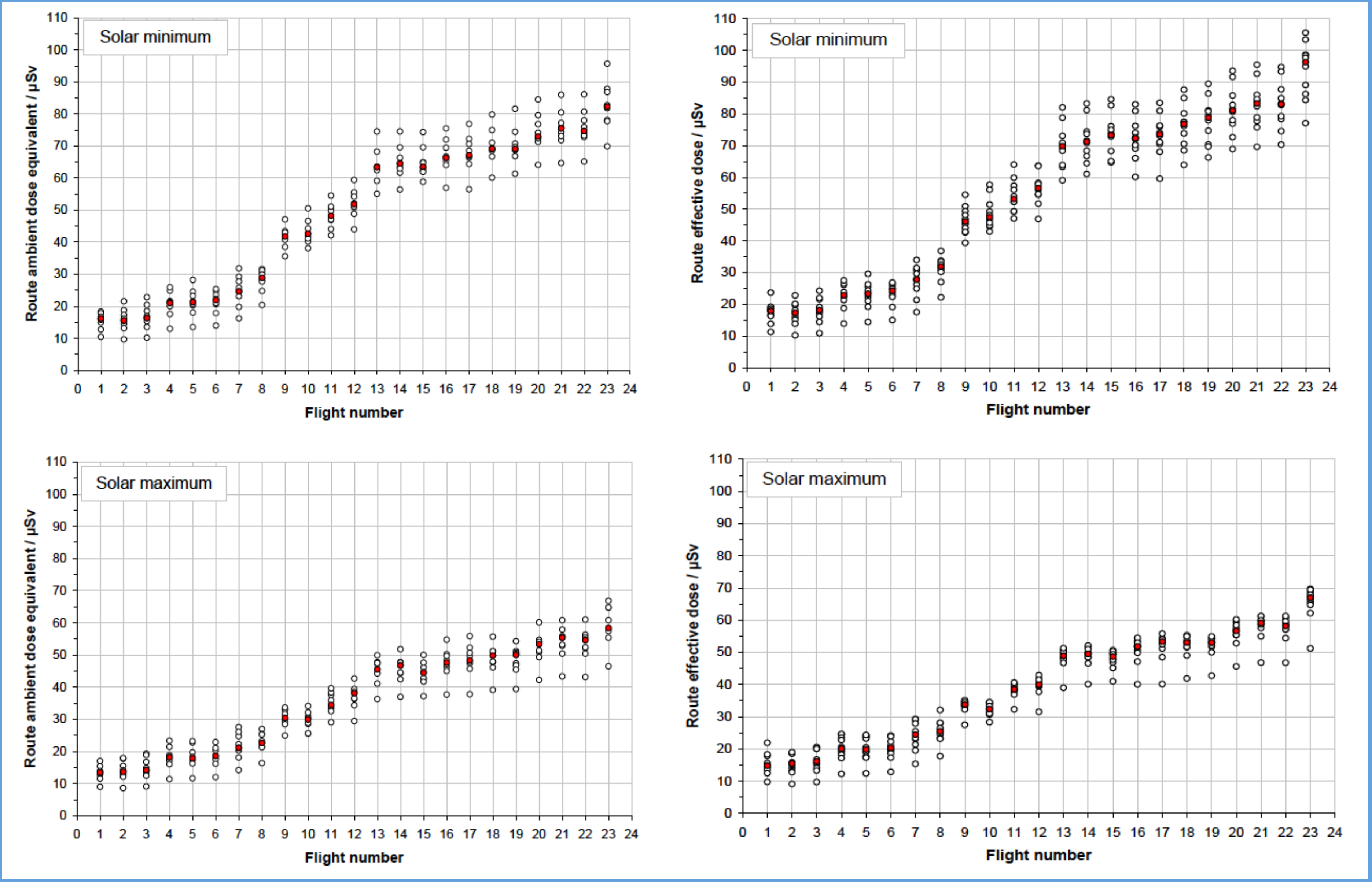

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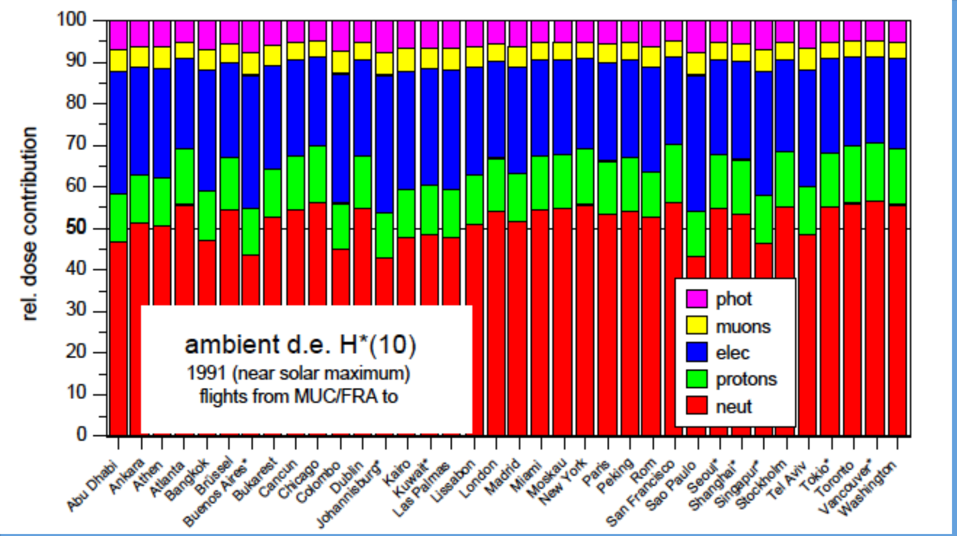
rel. dose contribution
ambient d.e. H*(10)
1991 (near solar maximum)
flights from MUC/FRA to
phot
muons
elec
protons
neut
Abu Dhabi
Ankara
Athen
Atlanta
Bangkok
Brüssel
Buenos Aires*
Bukarest
Cancun
Chicago
Colombo
Dublin
Johannisburg*
Kairo
Kuwait*
Las Palmas
Lissabon
London
Madrid
Miami
Moskau
New York
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Tokio*
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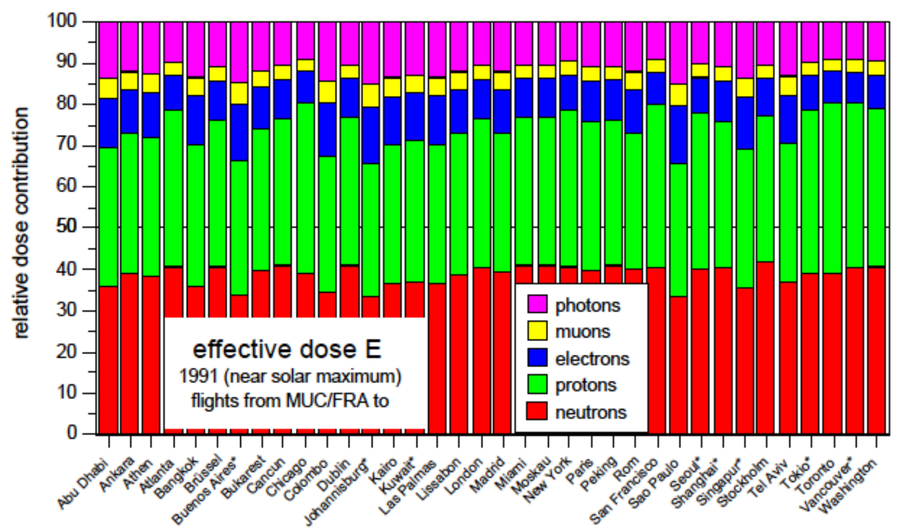
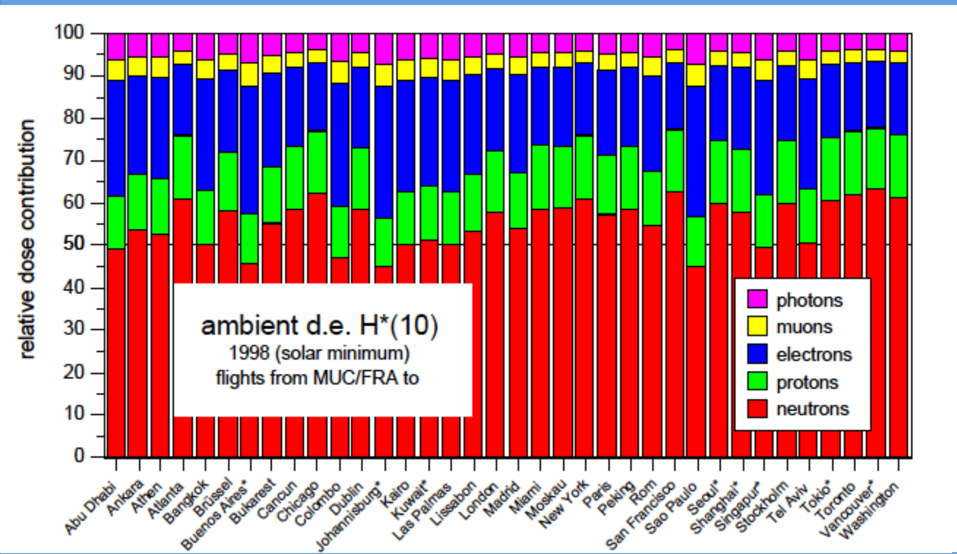
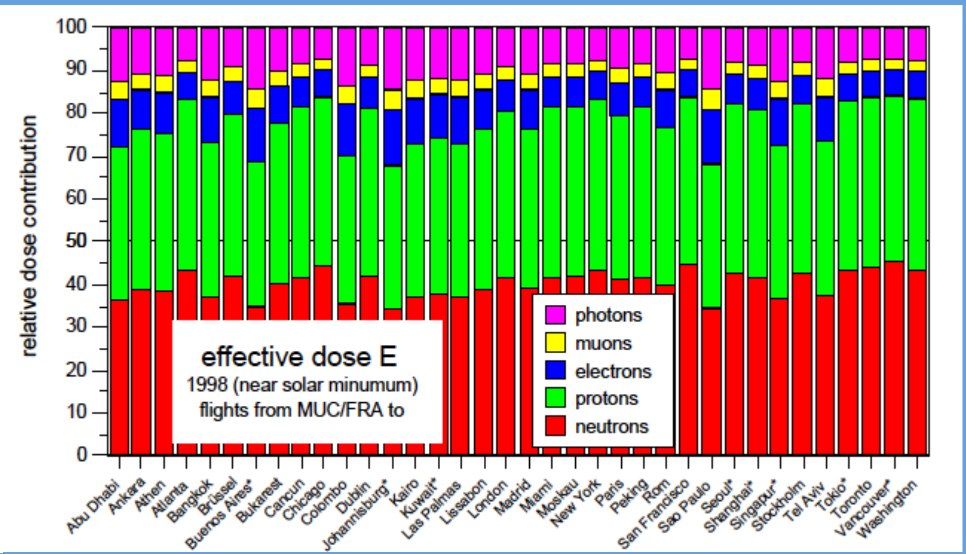
Vancouver*
Washington


relative dose contribution
effective dose E
1991 (near solar maximum)
flights from MUC/FRA to
photons
muons
electrons
protons
neutrons


relative dose contribution
ambient d.e. H*(10)
1998 (solar minimum)
flights from MUC/FRA to
photons
muons
electrons
protons
neutrons


relative dose contribution
effective dose E
1998 (near solar minumum)
flights from MUC/FRA to
photons
muons
electrons
protons
neutrons

The agreement between the codes is considered to be fully satisfactory.
Actually dose estimates in radiation protection generally include uncertainties no better than ±20 % to ±30 %.

This conclusion is further substantiated by the fact that most of these codes have also previously been validated by measurements (Lindborg, 2004), with an agreement between measured and calculated doses better than ±20 %.

In any case, it is recommended that any code to be used for dose assessment of radiation exposure due to secondary cosmic radiation at aviation altitudes should be validated by experimental data or by a comparison as presented in this report.

The agreement should be within ±30 % at a 95 % confidence level.

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★ **Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom** . . . .

Art. 35

3. For an undertaking operating aircraft where the effective dose to the crew from cosmic radiation is liable to exceed 6 mSv per year, the relevant requirements set out in this Chapter shall apply, allowing for the specific features of this exposure situation. Member States shall ensure that where the effective dose to the crew is liable to be above 1 mSv per year, the competent authority requires the undertaking to take appropriate measures, in particular:

(a) to assess the exposure of the crew concerned;

(b) to take into account the assessed exposure when organising working schedules with a view to reducing the doses of highly exposed crew;

(c) to inform the workers concerned of the health risks their work involves and their individual dose.

(d) to apply Article 10(1) to pregnant air crew.

(26) The exposure of air crew to cosmic radiation should be managed as a planned exposure situation. The operation of spacecraft should come under the scope of this Directive and, if dose limits are exceeded, be managed as a specially authorised exposure.

Article 10

Protection of pregnant and breastfeeding workers

1. Member States shall ensure that the protection of the unborn child is comparable with that provided for members of the public. As soon as a pregnant worker informs the undertaking or, in the case of an outside worker, the employer, of the pregnancy, in accordance with national legislation the undertaking, and the employer, shall ensure that the employment conditions for the pregnant worker are such that the equivalent dose to the unborn child is as low as reasonably achievable and unlikely to exceed 1 mSv during at least the remainder of the pregnancy.

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DLgs 230/95 capo II bis

Allegato 1 bis

Attività di volo

Criteri di individuazione delle attività di navigazione aerea

Sono soggette alle disposizioni del presente decreto le attività di navigazione aerea in relazione alle quali il personale navigante sia suscettibile di ricevere, per i voli effettuati, una dose efficace superiore a 1 mSv per anno solare;

è considerato suscettibile di ricevere una dose efficace superiore a 1 mSv per anno solare il personale navigante che effettui voli a quote non inferiori a 8.000 metri.

Modalità di valutazione e di registrazione della dose efficace

Nel caso in cui vengano effettuati voli a quote inferiori a 15.000 metri, la valutazione della dose ricevuta dal personale navigante è effettuata mediante appositi codici di calcolo, accettati a livello internazionale e validati da misure su aeromobili in volo su almeno due rotte di lungo raggio a latitudini diverse.

Nel caso in cui vengano, di regola, effettuati voli a quote uguali o superiori a 15.000 metri, la valutazione della dose efficace ricevuta dal personale navigante è eseguita oltre che avvalendosi dei suindicati codici di calcolo, mediante dispositivi di misura attivi in grado di rivelare variazioni significative di breve durata dei livelli di radiazioni ionizzanti dovuti ad attività solare.

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The radiation field at aviation altitudes is complex; thus, its dosimetry requires specialized techniques of measurement and calculation. The preferred approach would be to use devices that have an ambient dose equivalent response that is independent of the energy and the direction of the total field, or the field component to be determined.

It is generally necessary to apply corrections to the results of measurements, using data on the energy and direction characteristics of the field and the energy and angle ambient dose equivalent response of the device.

The field comprises mainly photons, electrons, positrons, muons, protons and neutrons. There is not a significant contribution to dose equivalent from energetic primary heavy charged particles (HZE) or fragments.

The electrons, positrons and muons are directly ionizing radiation and, together with indirectly ionizing photons and secondary electrons, interact with matter via the electromagnetic force.

Neutrons (and a small contribution from pions) interact via the strong interaction producing directly ionizing secondary particles.
Protons are both directly ionizing via the electromagnetic force and indirectly via strong force interactions.

At normal flight altitudes, the rounded percentage contributions to total ambient dose equivalent at temperate latitudes are:
electrons and positrons 25%;
muons 5%;
photons 10%;
neutrons 50%;
protons 10%

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For dosimetric purposes, it is convenient to divide the radiation field into the following components

- low LET (< 10 keV/μm)
- high LET (> 10 keV/μm)

This definition is based on the dependence of the quality factor on LET, which is unity below 10 keV/μm.

This separation between low and high LET particles can be applied to Tissue Equivalent Proportional Counters (TEPCs), and to other materials and detectors,

but the low LET/high LET threshold may vary between 5 keV/μm and 10 keV/μm.

$$Q(L) = \begin{cases} 1 & L < 10\ \mathrm{keV/\mu m} \\ 0.32\,L - 2.2 & 10 \leqslant L \leqslant 100\ \mathrm{keV/\mu m} \\ 300/\sqrt{L} & L > 100\ \mathrm{keV/\mu m} \end{cases} \qquad \text{(B.4.2)}$$

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unrestricted linear energy transfer
linear energy transfer
LET
for an ionizing charged particle, the mean energy imparted locally to matter along a small path through the matter, minus the sum of the kinetic energies of all the electrons released with kinetic energies in excess of *Δ*, divided by the length d*l*:

$$L_{\Delta} = \frac{dE_{\Delta}}{dl}$$

NOTE 1 This quantity is not completely defined unless Δ is specified, i.e., the maximum kinetic energy of secondary electrons whose energy is considered to be "locally deposited." Δ may be expressed in eV.

NOTE 2 Linear energy transfer is often abbreviated LET, but to which should be appended the subscript Δ or its numerical value.

NOTE 3 The unit of the linear energy transfer is J m^{-1}, a frequently used unit is keV μm-1.

NOTE 4 If no energy cutoff is imposed, the unrestricted linear energy transfer, L_{∞}, is equal to the linear electronic stopping power, S_{el}, and may be denoted simply as *L*.

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The low LET component comprises the following components:

- **directly ionizing electrons, positrons and muons**
- **secondary electrons from photon interactions**
- **most of the energy deposition by directly ionizing interactions of protons**
- **part of the energy deposition by secondary particles from strong interactions of protons and neutrons.**

The high LET component is from relatively short range secondary particles from strong interactions of protons and neutrons.

The relative contributions to the total ambient dose equivalent of low LET and high LET are generally similar in magnitude.

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Another common approach to classify the components of a radiation field is to distinguish between neutron and non-neutron components.
This approach is based on the detection technique applied since many measurement systems are not sensitive to neutron radiation.

- low LET (< 10 keV/μm) non neutron component
- high LET (> 10 keV/μm) neutron component

But neutron above 20 MeV produce an increasing contribution to low LET component.

The low LET and the non-neutron component can be measured using an ionization chamber, silicon-based detector, or scintillation detector or a passive luminescence or ion storage detector.

The neutron component can be measured using an extended range neutron survey meter or multi-sphere spectrometer; or a passive etched track detector, bubble detector or fission foil with damage track detector.

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How to validate codes and how to perform measurements?

Table 1: Equipment and detectors used to characterize radiation field on board civil aircraft

COMPONENT	DETECTOR TYPE	EQUIPMENT (DETECTOR) USED
All radiation	Active	Tissue equivalent proportional counter; Tissue equivalent ionization chamber; Set of low pressure GM-counters
Low LET radiation	Active	High pressure (Ar) ionization chamber; GM-counter based equipment; Scintillator based environmental dosemeters; silicon diodes
	Passive	Thermoluminescent detectors (CaF_2,$CaSO_4$,$Li_2B_4O_7$,LiF,Al_2O_3); photographic films
High LET radiation	Active	Rem counters (BF_3,ZnS:Ag+B); Bonner spheres; Organic scintillator-based systems; Proton recoil counter
	Passive	Activation detectors; nuclear emulsions; Fission foils; Superheated drop detectors; Solid state nuclear track detectors (PADC/CR39/ Makrofol)

Table A.2:

Detector Type	Mainly used to measure	Lower Detection Limit[(a)]	Advantages and Shortcomings
Thermoluminescent detectors	Low LET ionizing radiation	10 μSv	LiF:Mg, Cu, P highly sensitive for low LET radiation
Photoluminescent detectors	Low LET ionizing radiation	10 μSv	Highly sensitive for low LET radiation
Bubble detectors	Neutrons with energy below 20 MeV	10 μSv	Sufficiently sensitive for single intercontinental flight measurement; direct reading
Polycarbonate detectors	Neutrons in energy range 1-50 MeV	≤ 100 μSv	Useful for long integrated exposures.Sensitive to alpha particles and heavier particles
PADC/CR39 detectors	Neutrons, protons and heavy ions	≤ 100 μSv	Useful for long integrated exposures. Sensitive to protons and heavier particles
Bismuth detectors	High energy neutrons and protons (> 50 MeV)	≤ 100 μSv	Threshold detectors for the measurements of high energy neutrons/protons
Stack of thin films of cellulose nitrate detectors - LR-115	HZE particles Heavy ions with Z ≥ 2	One particle per 200 cm^2	A multi-element stack with simple scanning procedures

(a) Three times the standard deviation of the background.

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The two main types of energy deposition spectrometers are gas-filled devices, in particular tissue equivalent proportional counters (TEPCs), and solid state (normally silicon) devices

A tissue equivalent proportional counter (TEPC) is sensitive to directly ionizing particles and to indirectly ionizing particles via the charged secondary particles created by them in the walls of the counter.

The sensitive volume is filled with a gas of chemical composition similar to tissue, at a low pressure in order to simulate a biological site of a few microns.

Although ideally of spherical symmetry, TEPCs are often cylindrical. Incident radiation produces electrons in the gas which are collected on the central anode, when an electric field is applied between the anode and the wall of the detector.
Each event (or particle track through the gas) produces an output signal whose magnitude is proportional to the initial energy deposited.

Each event detected is analysed using a pulse height analysis method and stored to produce the lineal energy distribution spectrum, d(*y*); *y* is the energy deposited divided by the average chord length of the detector.
For many practical purposes, *y* is used as an approximation to LET.

The sum of the deposited energy for each event divided by the mass of gas provides the absorbed dose.
The dose equivalent may be calculated by folding the absorbed dose distribution with the quality factor.

Solid state energy deposition spectrometers measure the energy deposited in one or more silicon detectors.
If a single detector is used, a pulse height distribution is recorded. Alternatively, several detectors with differing LET thresholds may be used.
The total dose to silicon and its distribution in LET can be related to dose and dose equivalent to tissue.
Suitable characterization and calibration allows ambient dose equivalent to be determined.

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The recombination chamber makes use of the fact that the initial recombination of ions in the gas cavity of the ionisation chamber depends on local ionisation density. The latter can be related to LET and provides information on radiation quality of the investigated radiation fields [37]. The saturation current of the recombination chamber is proportional to the total absorbed dose, *D*. Measurements of ionisation current at a specially chosen “recombination“ voltage enables determination of a recombination index of radiation quality and thus the dose equivalent, and, after, characterization and calibration, ambient dose equivalent

Organic and inorganic scintillators are commonly used to detect photons and charged particles with high detection efficiency. Owing to the high hydrogen and carbon content, large volume organic scintillators are also used as neutron detectors with a neutron detection efficiency depending of the thickness of the scintillator material. Therefore, small sized scintillation counters (scintillator thicknesses of the order of 1 cm) used as dosemeters usually do not have sufficient detection efficiency for neutron dosimetry, but organic scintillators of sufficient size (thicknesses of a few 10 cm) can be used for spectrometric purposes

Devices for low LET/non-neutron

Ionization chambers
Geiger Müller counters
Electronic personal dosemeters

Devices for high LET/neutron component

Moderated devices
Spectrometers

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Moderate-and-capture devices employing a thermal-neutron detector surrounded by an hydrogenous moderator are frequently used to determine $H^*(10)$ in neutron fields.

Such devices, often called rem meters, generally show a decreasing dose equivalent response with increasing energy in the MeV region.

This is true both for homogeneous spheres (including multi-sphere spectrometer detectors) and for detectors with neutron absorbing layers to simulate the required dose equivalent response. In cosmic radiation neutron monitors, lead is used to "convert" high-energy particles, especially neutrons, into multiple lower-energy neutrons which are readily moderated and detected.

This converter principle has been implemented in survey instruments for routine use at high-energy accelerators in the LINUS (Long Interval Neutron Survey-meter), which uses a lead converter, a similar device (NM500X), and the WENDI (Wide Energy Neutron Detection Instrument), which uses tungsten as both a neutron generator material above 8 MeV and as an absorber below several keV.

Of the many kinds of active neutron spectrometers, two have high enough sensitivity to measure the cosmic radiation neutron energy distribution in aircraft:

moderate-and-capture multi-detector (multi-sphere) spectrometers
recoil-proton spectrometers using organic liquid or solid scintillators.

Only multi-sphere spectrometers have been used to make measurements in aircraft.

Passive detectors are suitable to measure ambient dose equivalent integrated over flights or a number of flights.

The sensitivity and intrinsic background need to be considered.

The basic types of passive devices for high LET/neutron component are track etch detectors and superheated emulsions (also known as bubble damage or superheated drop detectors

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EURADOS Working Group 11 High Energy Radiation Fields

The motivation is to increase the knowledge and expertise regarding field characterization and dose assessment in various activities where high energy radiation fields are found, like in medicine, research, civil aviation, and space.

AIMS

- To measure and characterize high energy fields for assessment of human exposure and for instrument calibration
- To determine the instrument response in high energy fields, especially in pulsed fields
- To assess the dose due to solar particle events
- To measure cosmic radiation at ground level and at aviation altitudes
- To compare the different systems (instruments, calculation codes) used for high energy field dosimetry.

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On board of aircraft

At labs at low latitude (south pole north pole)

At labs in Antartica

At lab on the top of mountains

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Marambio Base (64° 13’S –56°43’W) Antartic

Cervino 3480 above see level Italy

Chacaltaya 5400 above see level Bolivia

Ny-Ålesund are 78°N55'24'' and 11°E55'15'

Jungfraujoch, 3580 m above sea level Switzerland

...mpo delle Radiazioni Ionizzanti,
...nti”

Dr Adolf...
adolfo.e...

Zugspitze mountain at 2650 m above sea level Germany

CORA PROJECT

Neutron detector inter-comparison

August - November 2014

Testa Grigia Laboratory Cervinia – Italy

3480 m asl   45°56’N   7°42’E

Participant Institutions

INFN Torino
LNF Frascati
Politecnico Milano

INAF Roma

Neutron detectors *H* (mSv)*

Rem Counter Atomtex	*(0.025 eV- 14 MeV)*
Extended Rem Counter	*(0.025 – 5 GeV)*
Passive Rem Counter CR 39	*(0.025 eV- 1GeV)*
Portable Neutron Monitor	*cosmic ray variability*

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