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DOSIMETRY OF COSMIC RADIATION:
A CHALLENGE FOR METROLOGY

Jean-François BOTTOLLIER-DEPOIS, IRSN, France

MEMBRE DE
ETSON

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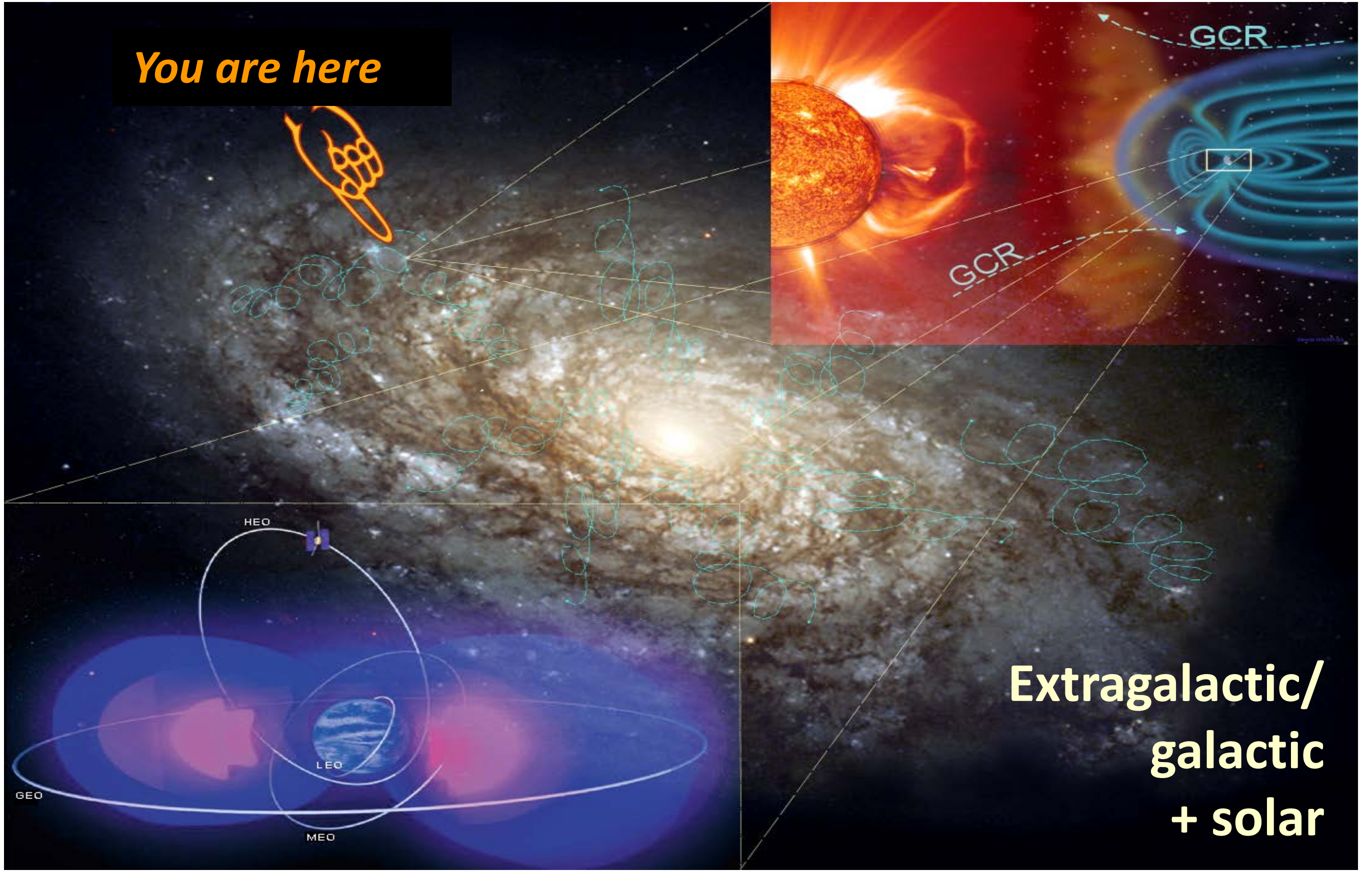
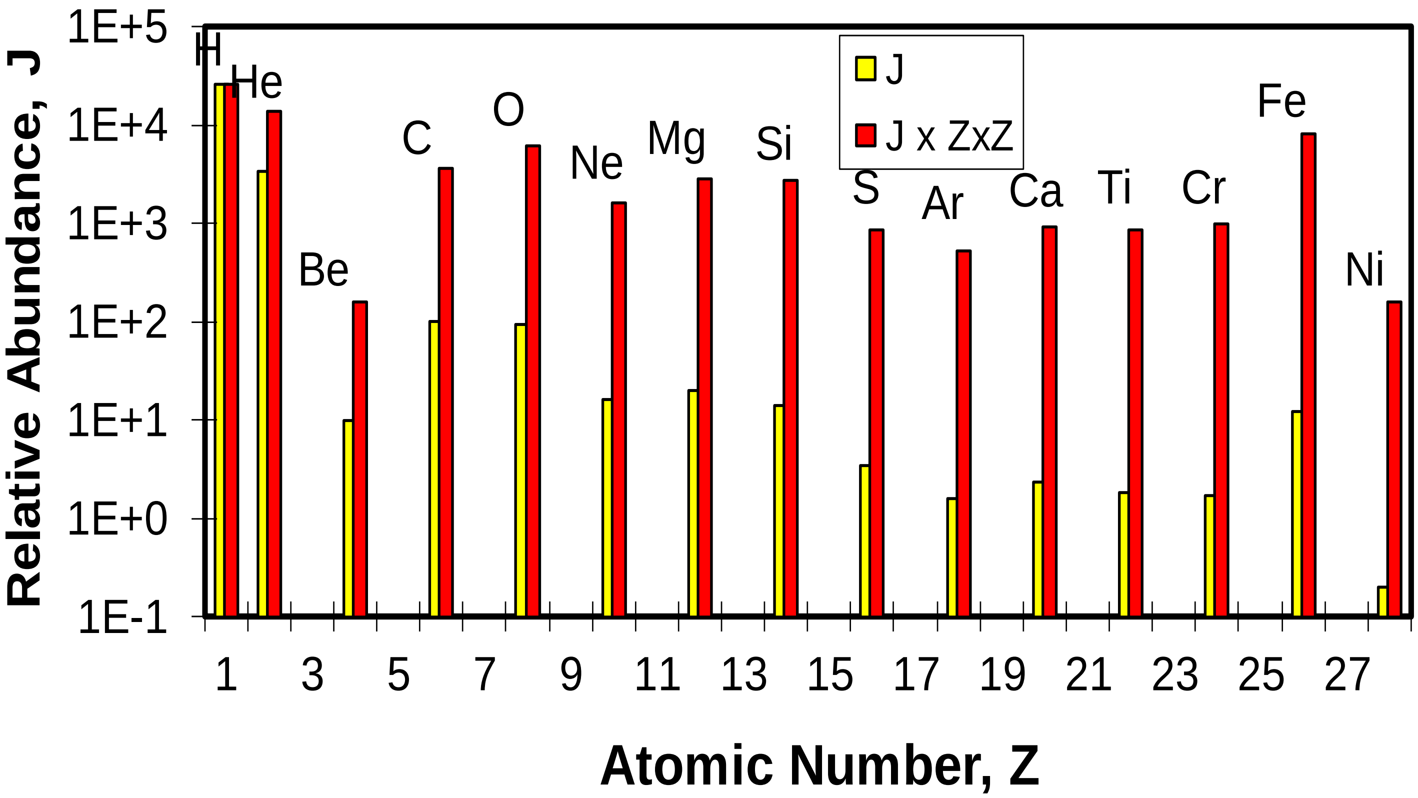
CHARACTERISTICS OF COSMIC RADIATION

MEMBRE DE ETSON

Origin of Cosmic Radiation



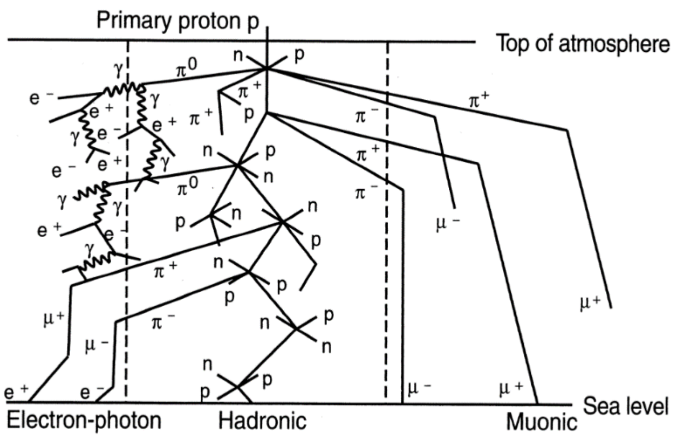
Composition of cosmic radiation

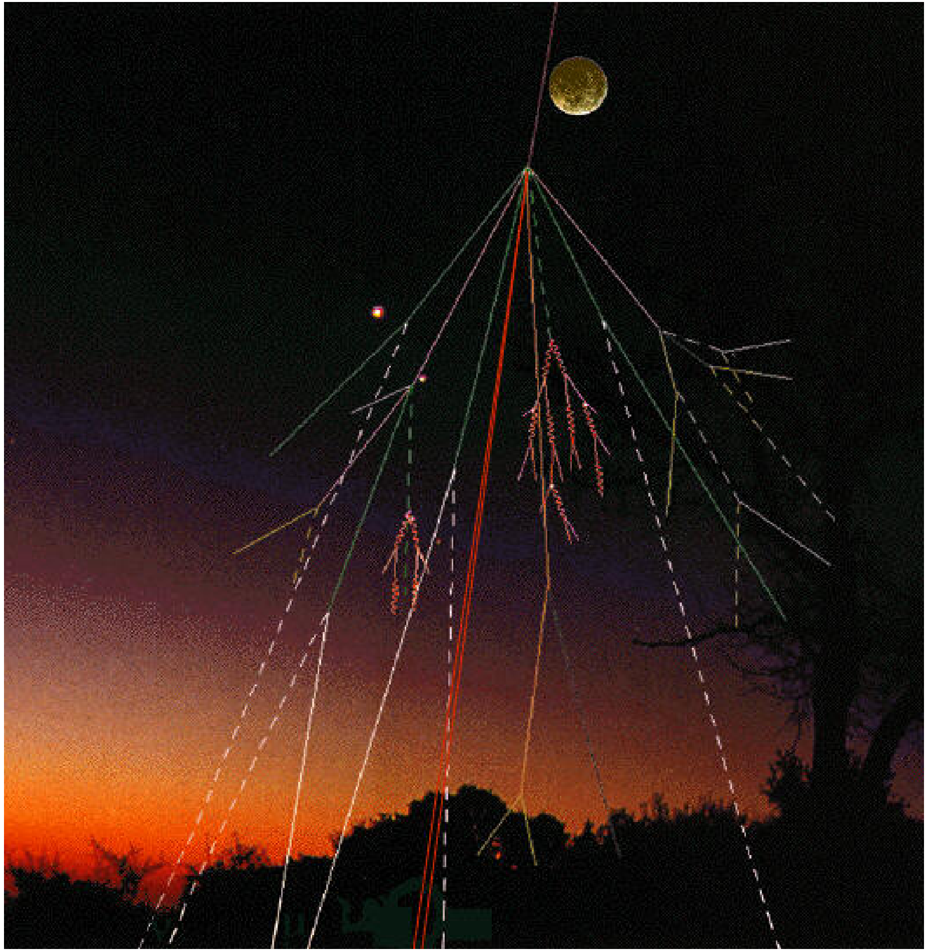


Interaction with the atmosphere

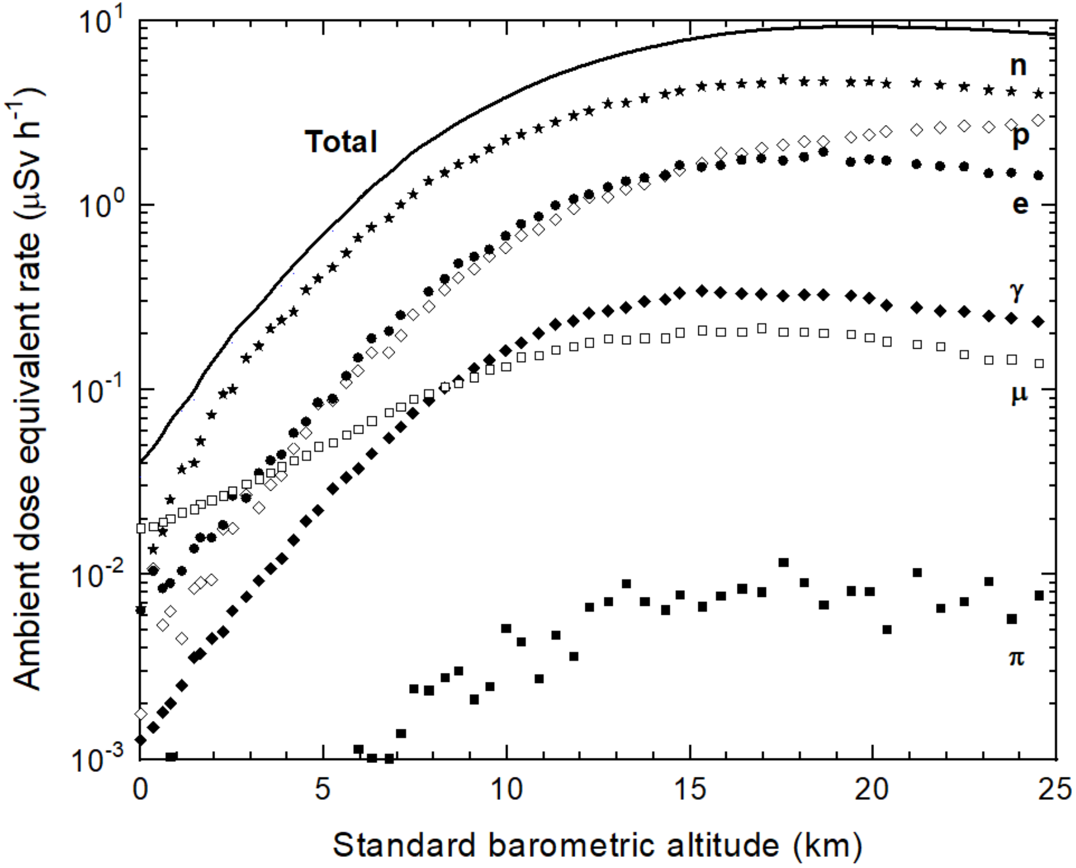
Composition of the CR at the top of the atmosphere (~35 km)

electrons/positron: 2%
protons: 85%
helium nucleus: 12%
heavier ions: 1 %





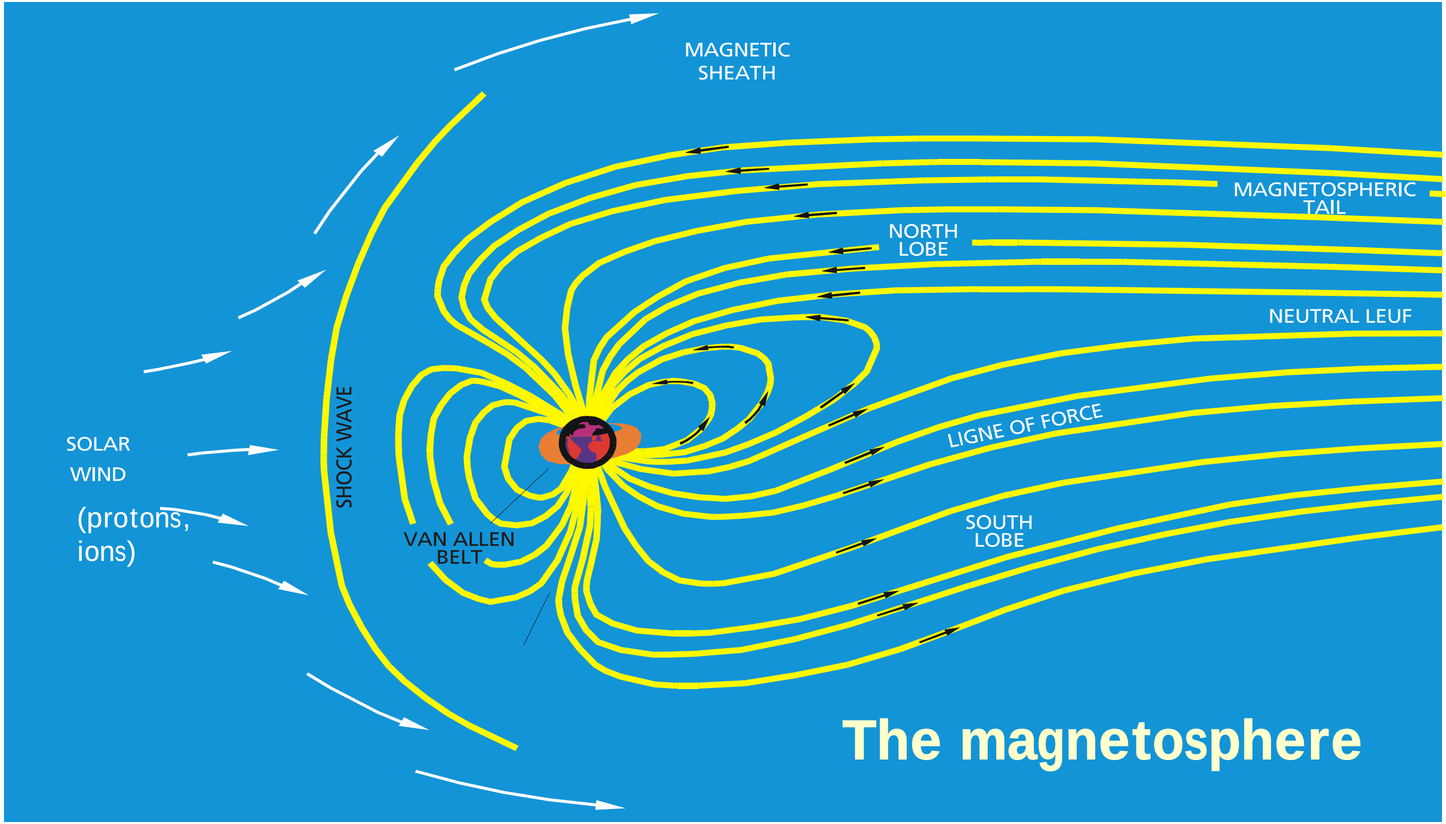
Protection = function (atmosphere thickness)



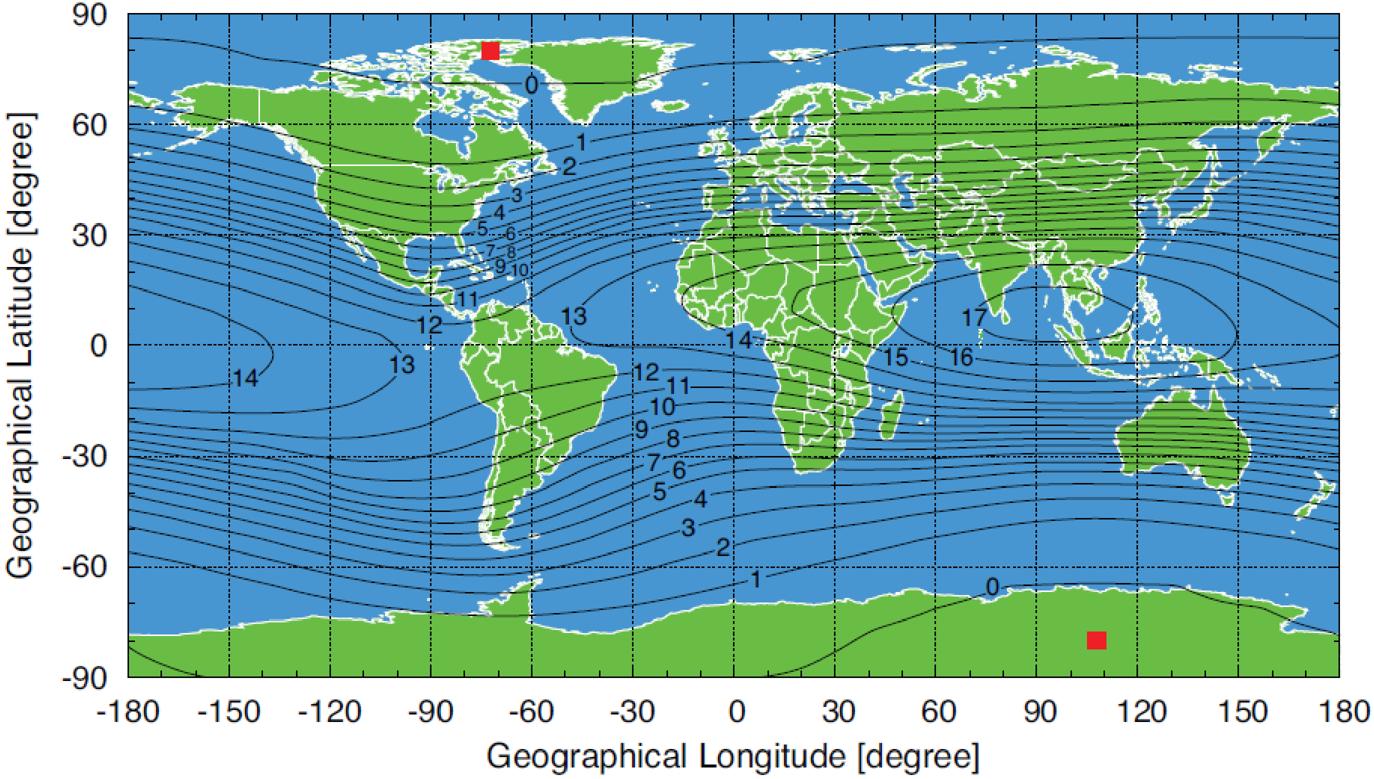
Ambient dose equivalent rate as a function of **standard barometric altitude** at 2 GV vertical geomagnetic cutoff rigidity and mid solar cycle, for various particles of the cosmic radiation field in the atmosphere calculated using the Monte Carlo radiation transport code FLUKA (ICRU, 2010).

From EURADOS report 2021-03

Interaction with the Earth's magnetic field



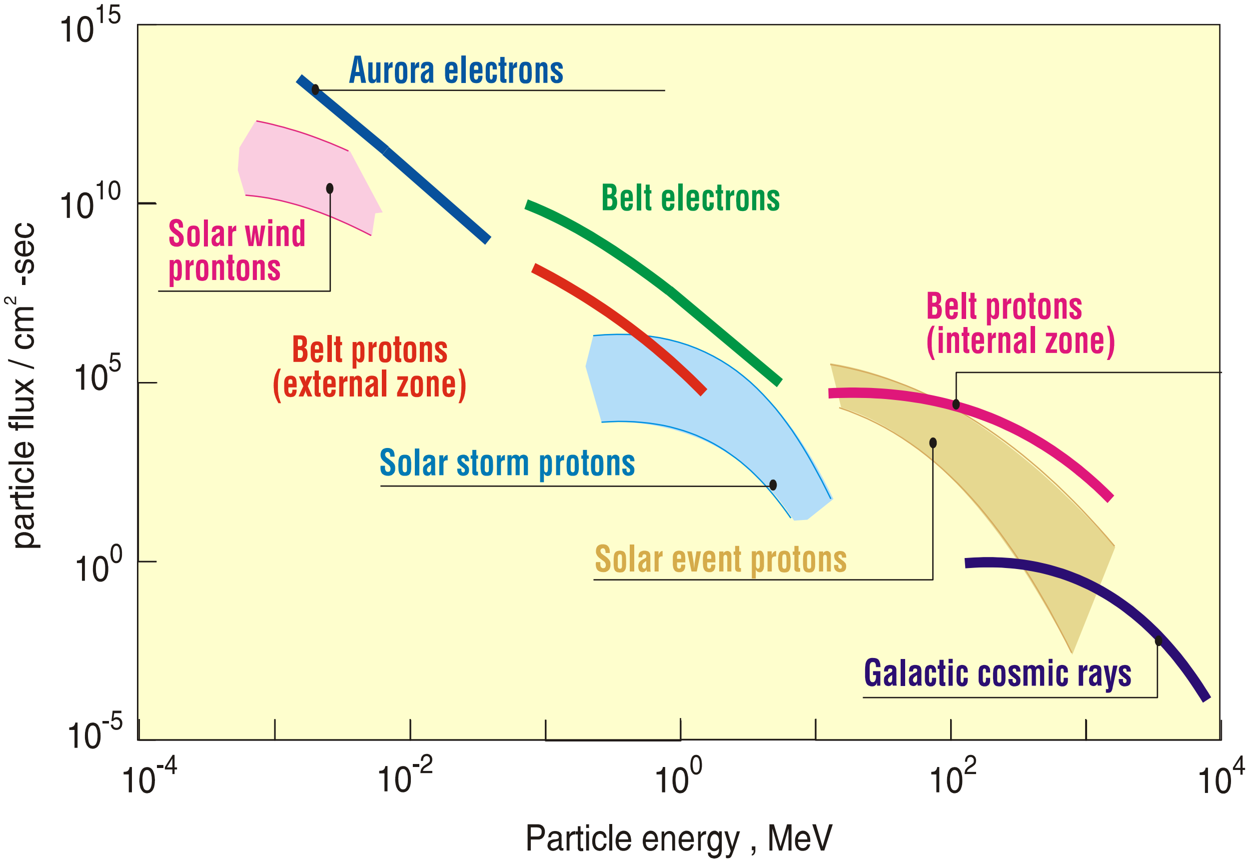
Protection = function (geomagnetic position)



Geomagnetic vertical cutoff rigidity (in GV) contour lines for years 2010 to 2015, and quiescent geomagnetic conditions *(Finlay, 2010a, b; Macmillan, 2011)* and the model by Tsyganenko, 1989. Red squares indicate the positions of the geomagnetic poles in the 10^{14} MeV year 2010 *(Pioch, 2012)*

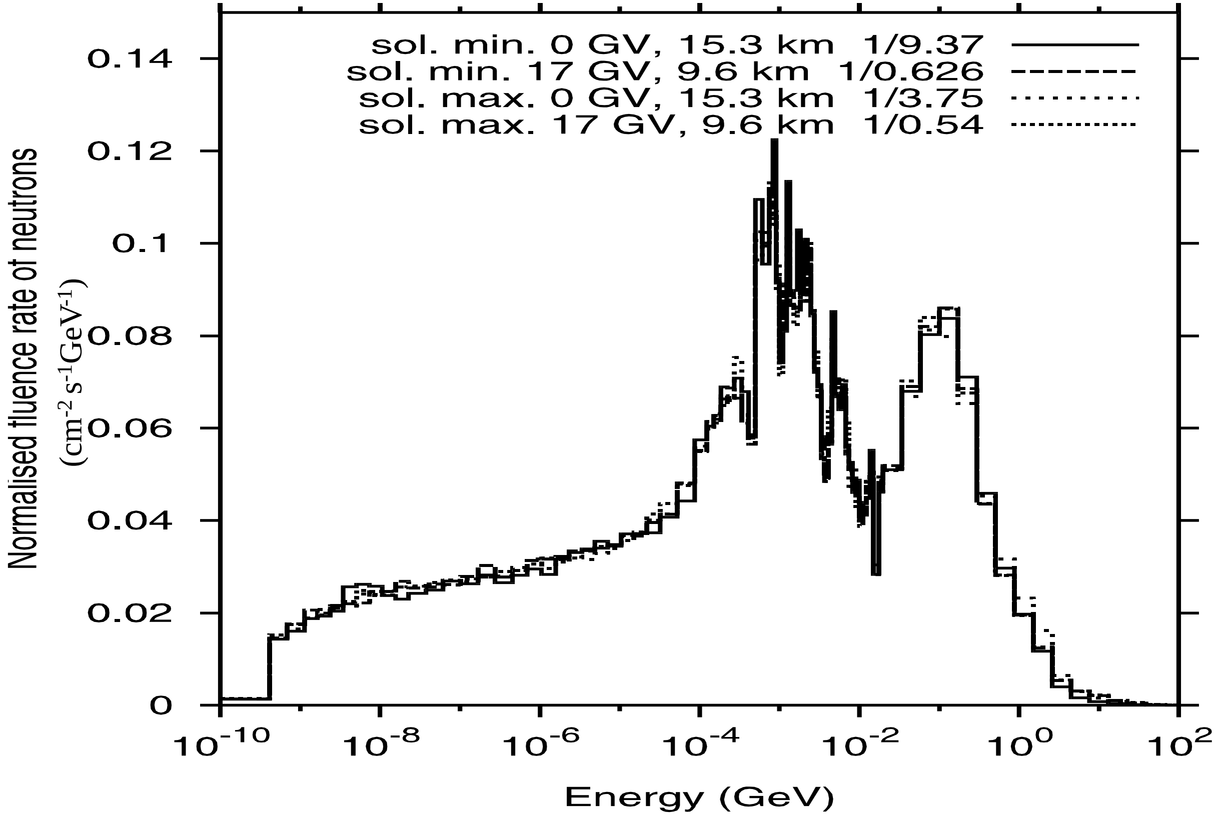
From EURADOS report 2021-03

Energy spectrum of the various components of cosmic radiation



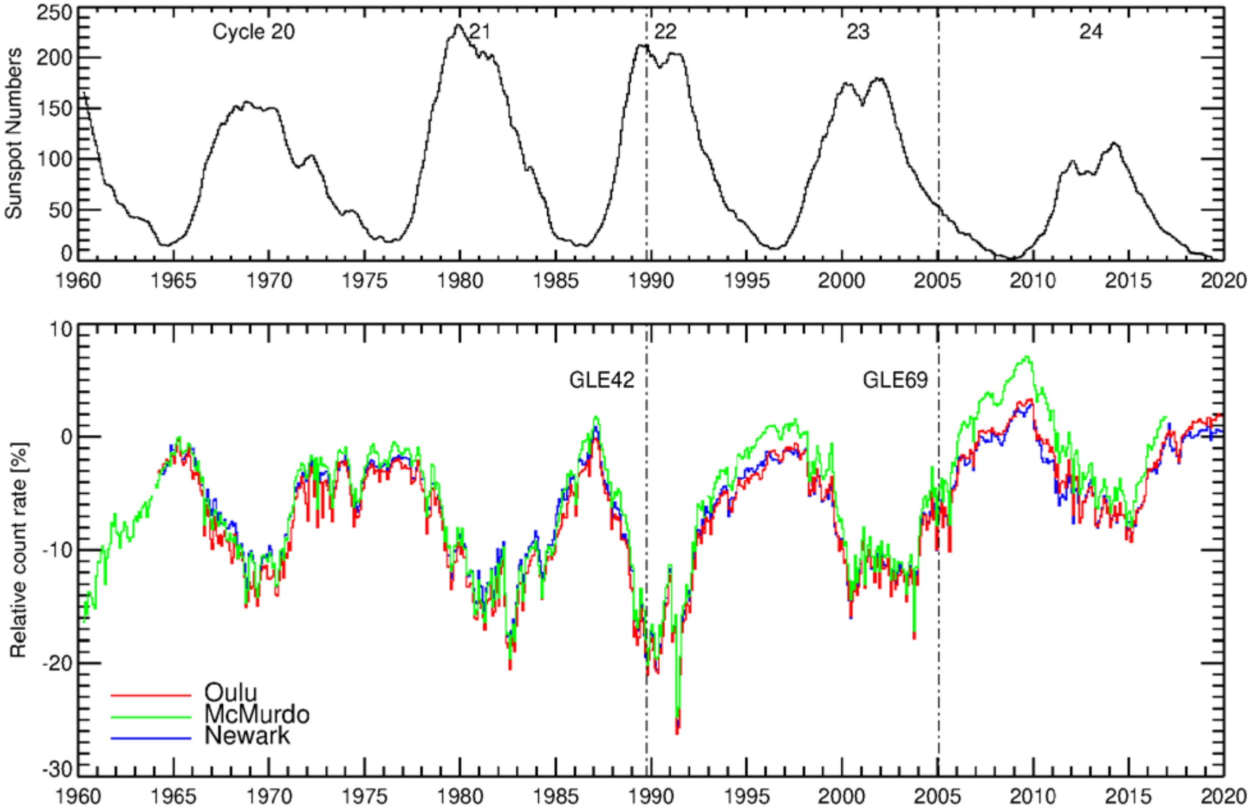
Up to 10^{14} MeV
with 1 $km^{-2}.century^{-1}$!

Neutron spectra at aircraft flight altitudes



(SCHRAUBE, et al. (2000) Proc. 10th IRPA)

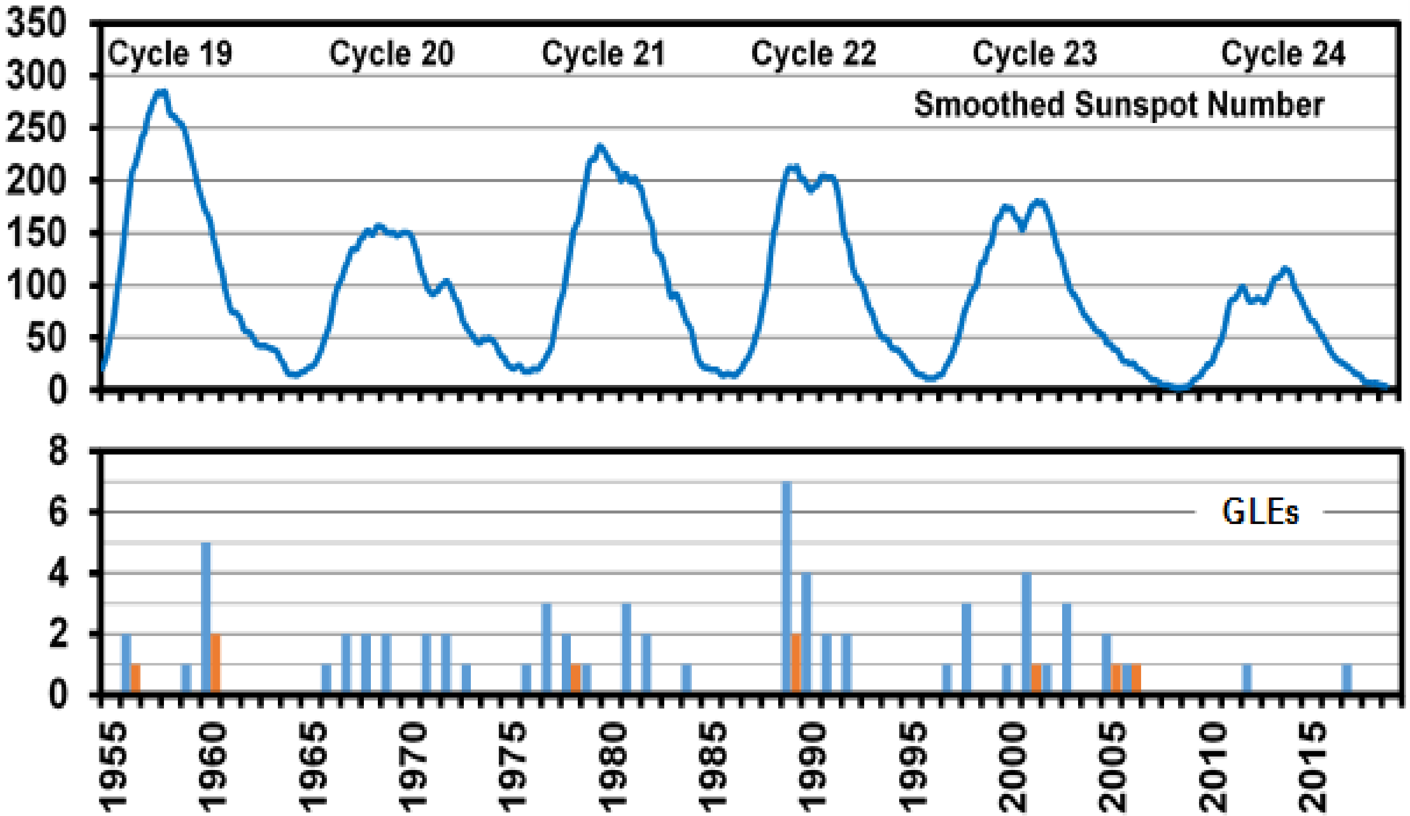
Solar activity cycle



Smoothed sunspot numbers *(top panel),* pressure corrected monthly **counting rates of the neutron monitor stations** Oulu, McMurdo, and Newark *(bottom panel)* for the years 1960-2019. The neutron monitor count rates are expressed in relative units with respect to May 1965. The vertical dashed-dotted lines indicate the time of the GLEs on 29 September 1989 (GLE42) and on 20 January 2005 (GLE69). The neutron monitor at McMurdo stopped operation in January 2017 and was moved to Jang Bogo

From EURADOS report 2021-03

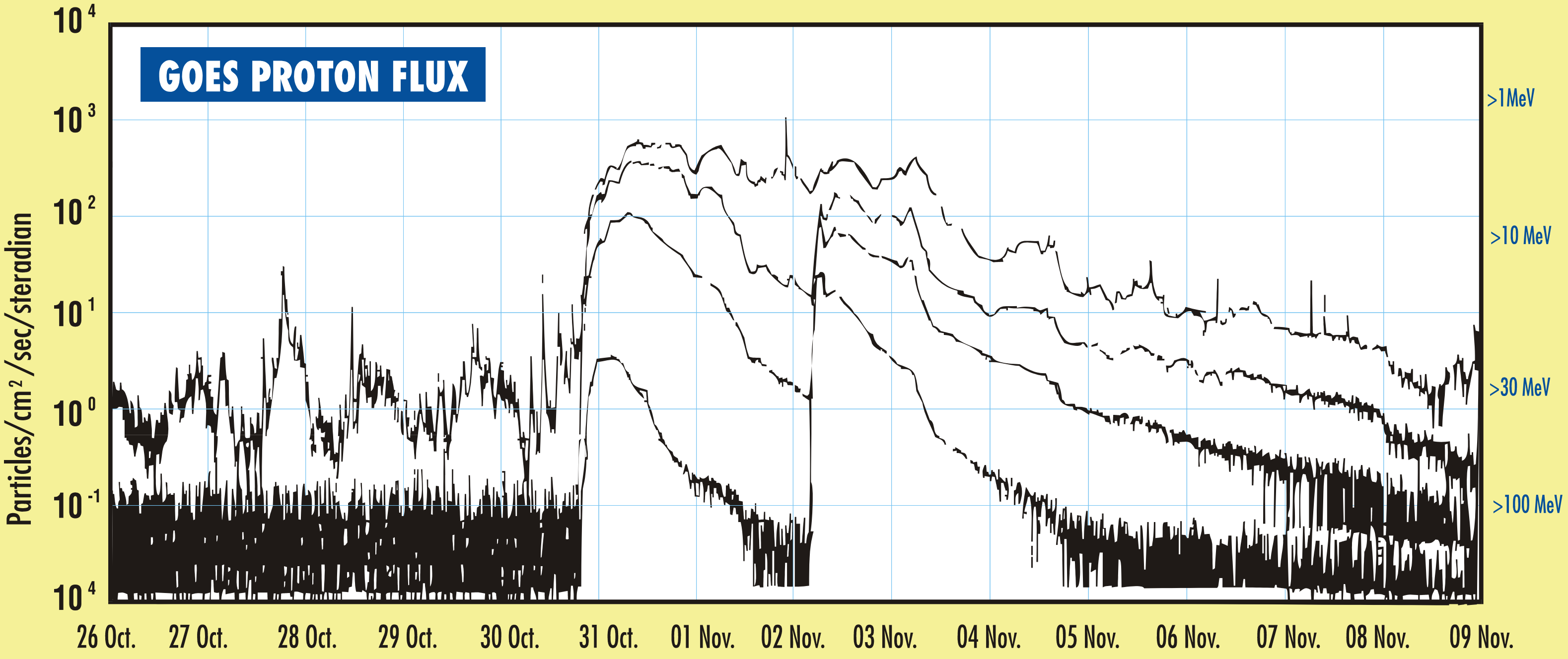
Ground Level Event (GLE) frequency



Smoothed sunspot number *(top panel,* source: WDC-SILSO, Royal Observatory of Belgium, Brussels) and the **number of GLEs per year** *(bottom panel)* during the solar cycles 19 - 24 (until December 2017). Blue bars: all GLES, red bars: GLEs with amplitude >70%. Figure after Shea and Smart, 1993 (Shea, 1993)

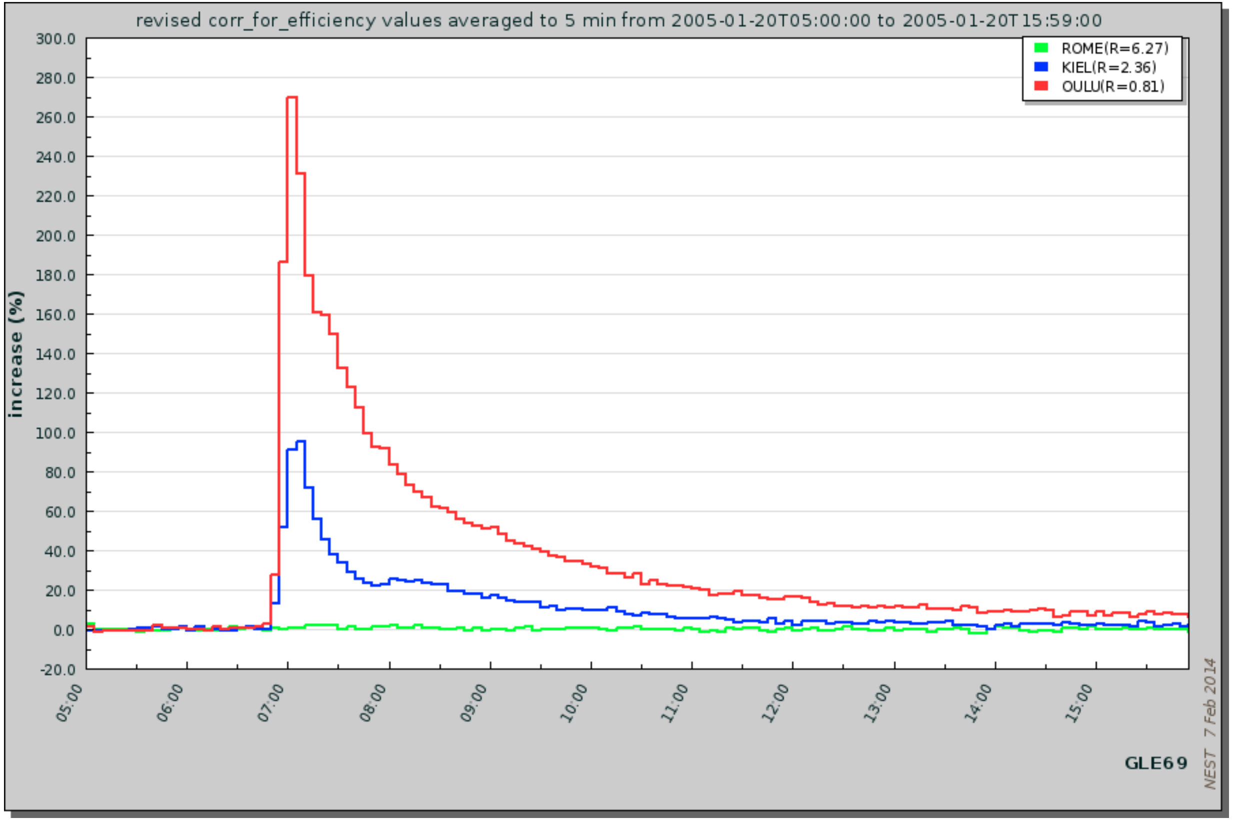
From EURADOS report 2021-03

Solar eruption: proton flux measured on the GOES satellite



(Source: Space Environment Services Center report N°896 - 897 1992)

GLE69: ground neutron monitors measurements



Relative 5 minutes **count rate values for the neutron monitor stations** Oulu (red), Kiel (blue), and Rome (green) plotted with NEST from www.nmdb.eu for the time interval 05:00-16:00 UT on 20 January 2005 (GLE69)

From EURADOS report 2021-03

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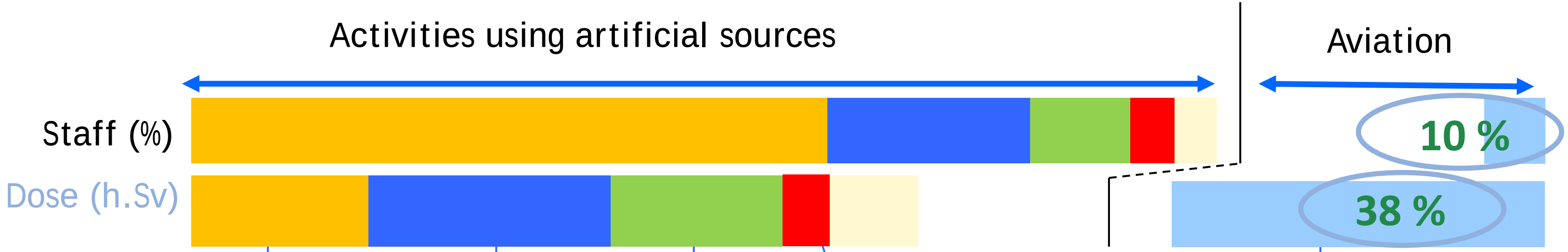
DOSIMETRY IN AVIATION

Context and challenges

- The exposure at aviation altitude is mainly due to GCR secondaries
- Solar particle events (SPE) contribute sporadically to the exposure onboard aircrafts
  - *4 Ground Level Events (GLE) since 2000 with a “visible” effect*
- Occupational exposure for aircraft crews is assessed using models
- Measurements are needed mainly for validation of models, in particular for GLEs
- Specific approaches are defined for characterisation and calibration of instruments

Annual dose for workers in different domains of acitivity *(in France)*



Medical
18 %
0,49 mSv

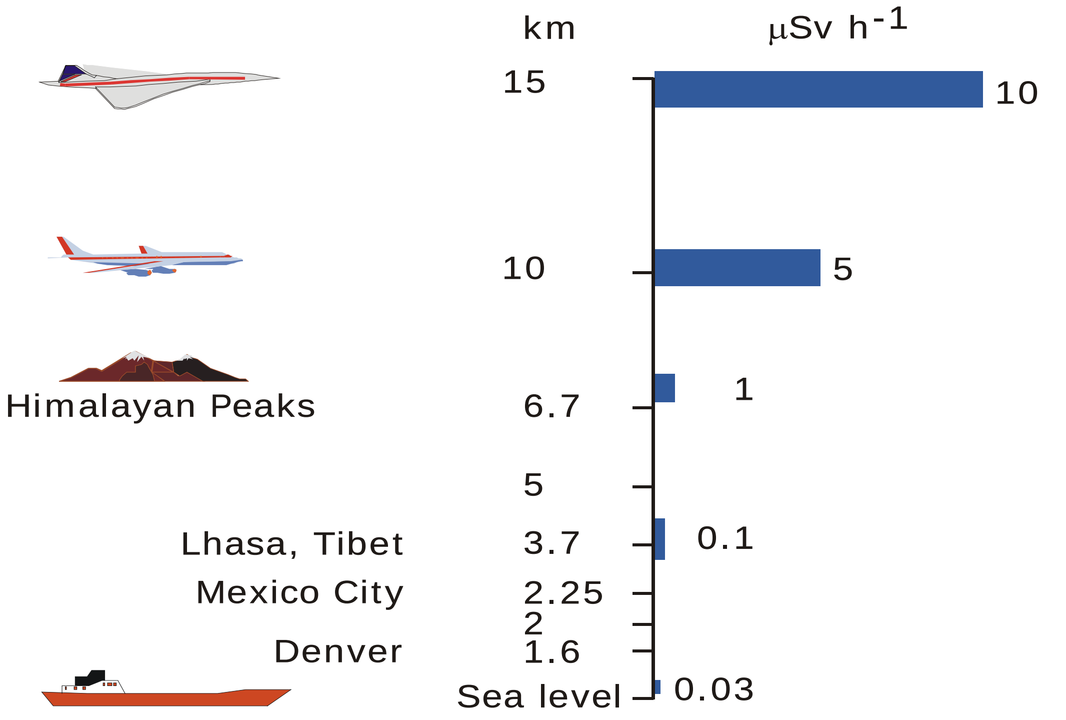
Nuclear
25 %
1,16 mSv

Industry
18 %
1,54 mSv

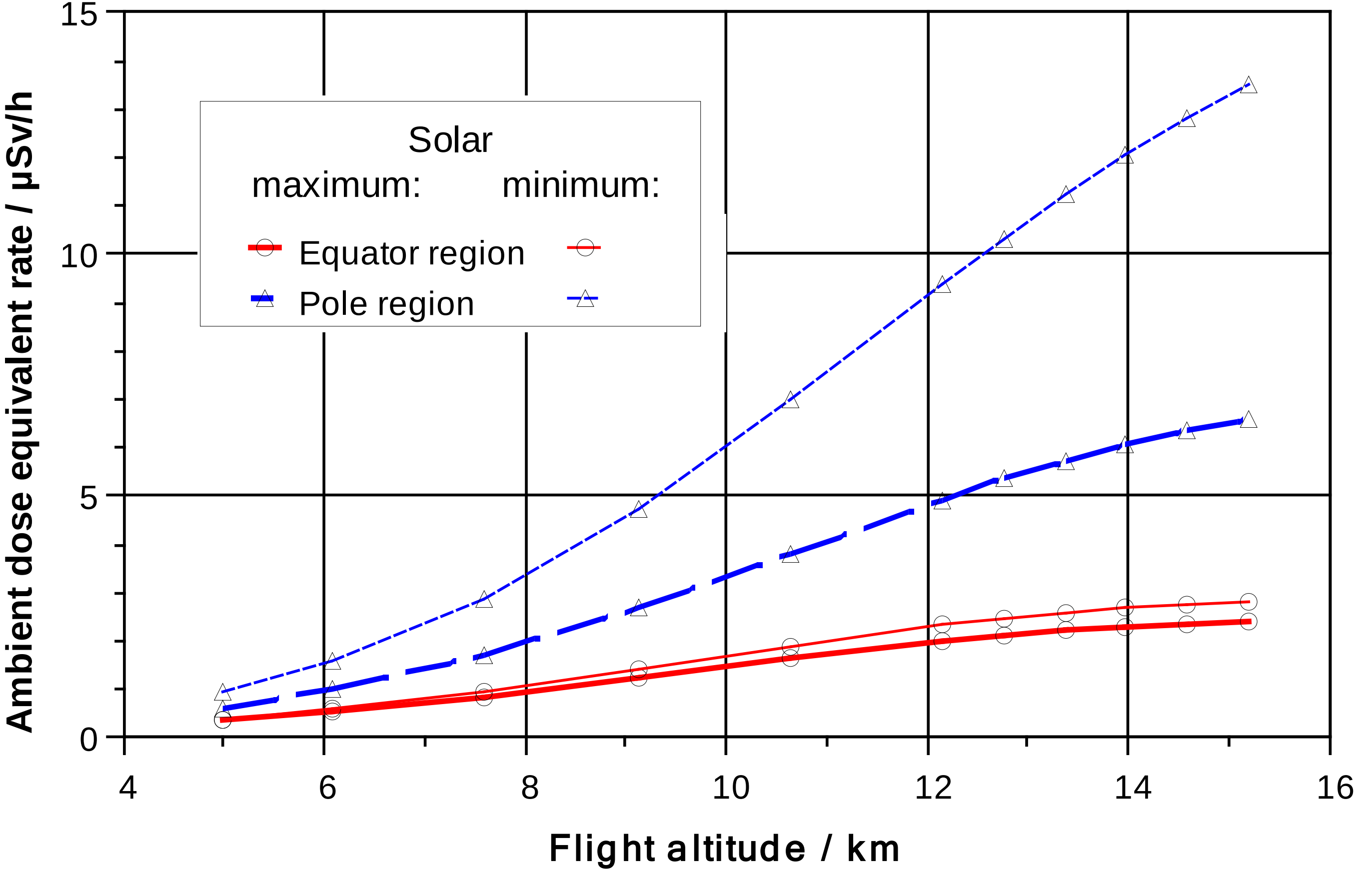
Research
0,5 %
0,33 mSv

Aviation
38 %
1,9 mSv

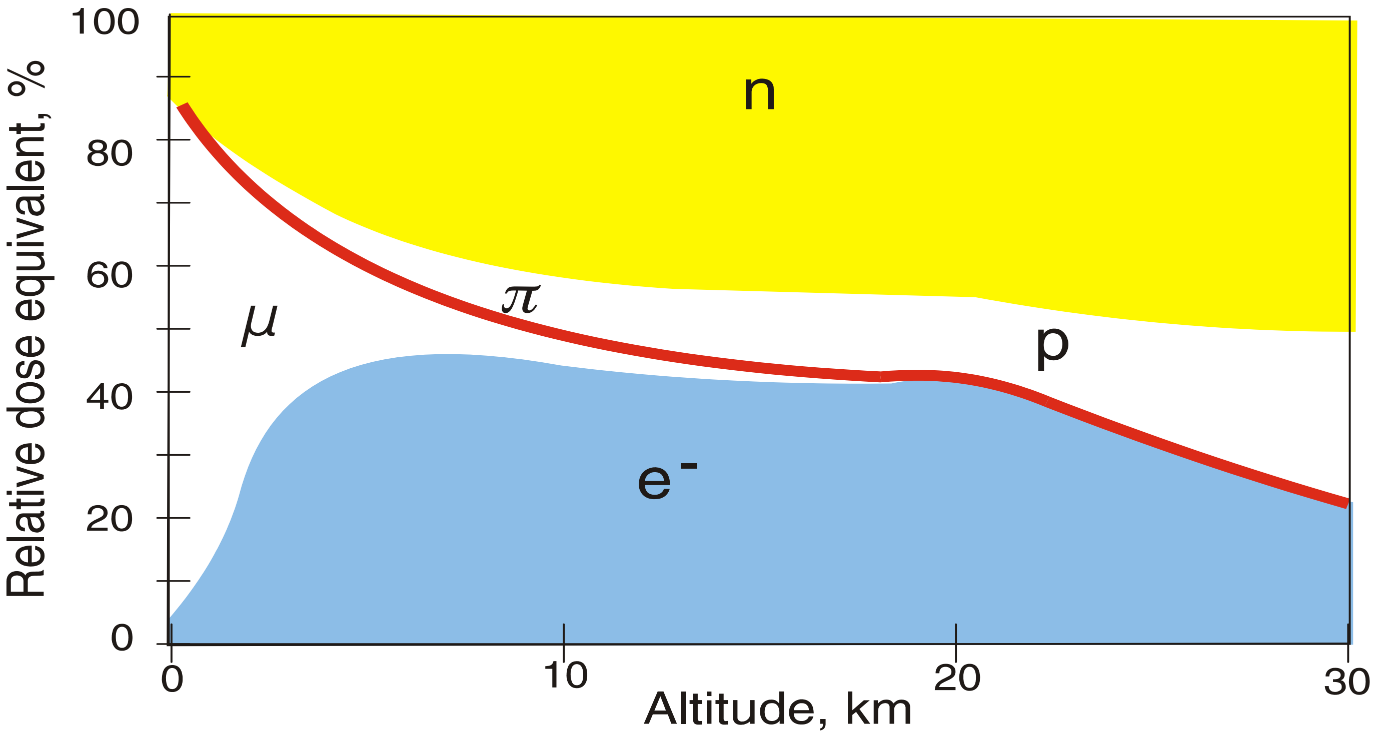
Dose rate from ground level to aviation altitude



Dose as a function of altitude

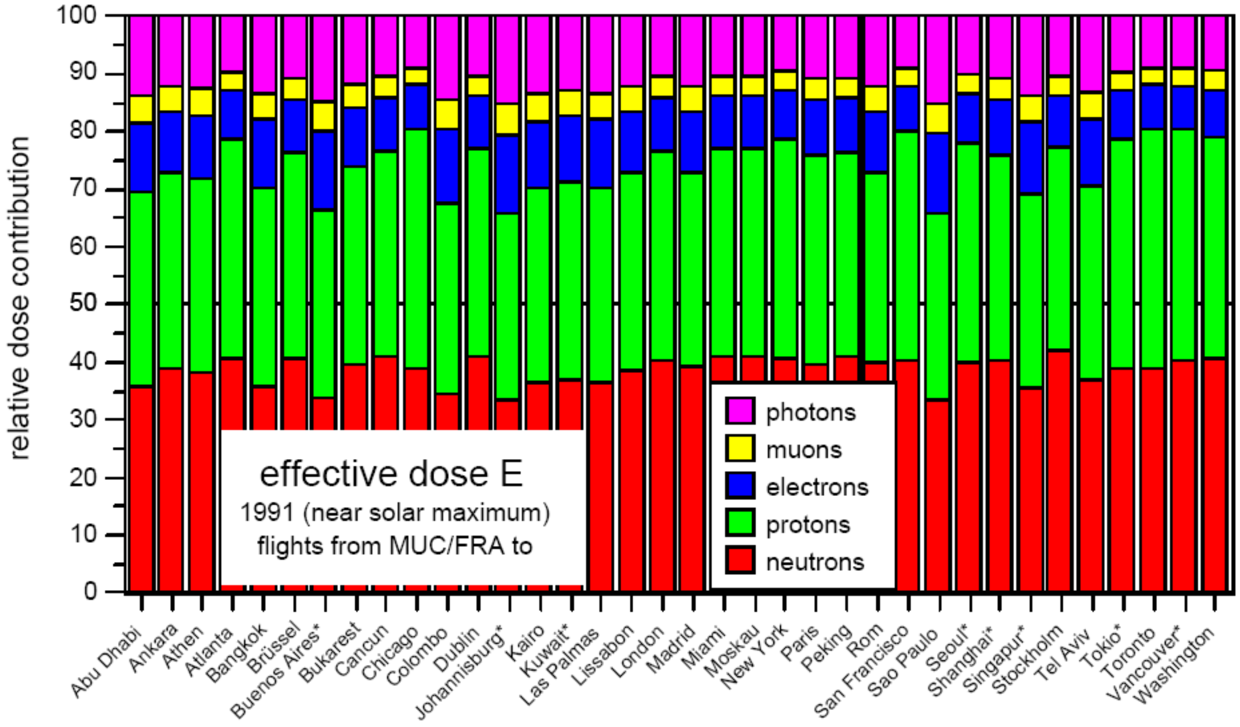


Contribution of the main components to the dose in the atmosphere



EURADOS report 1996-01

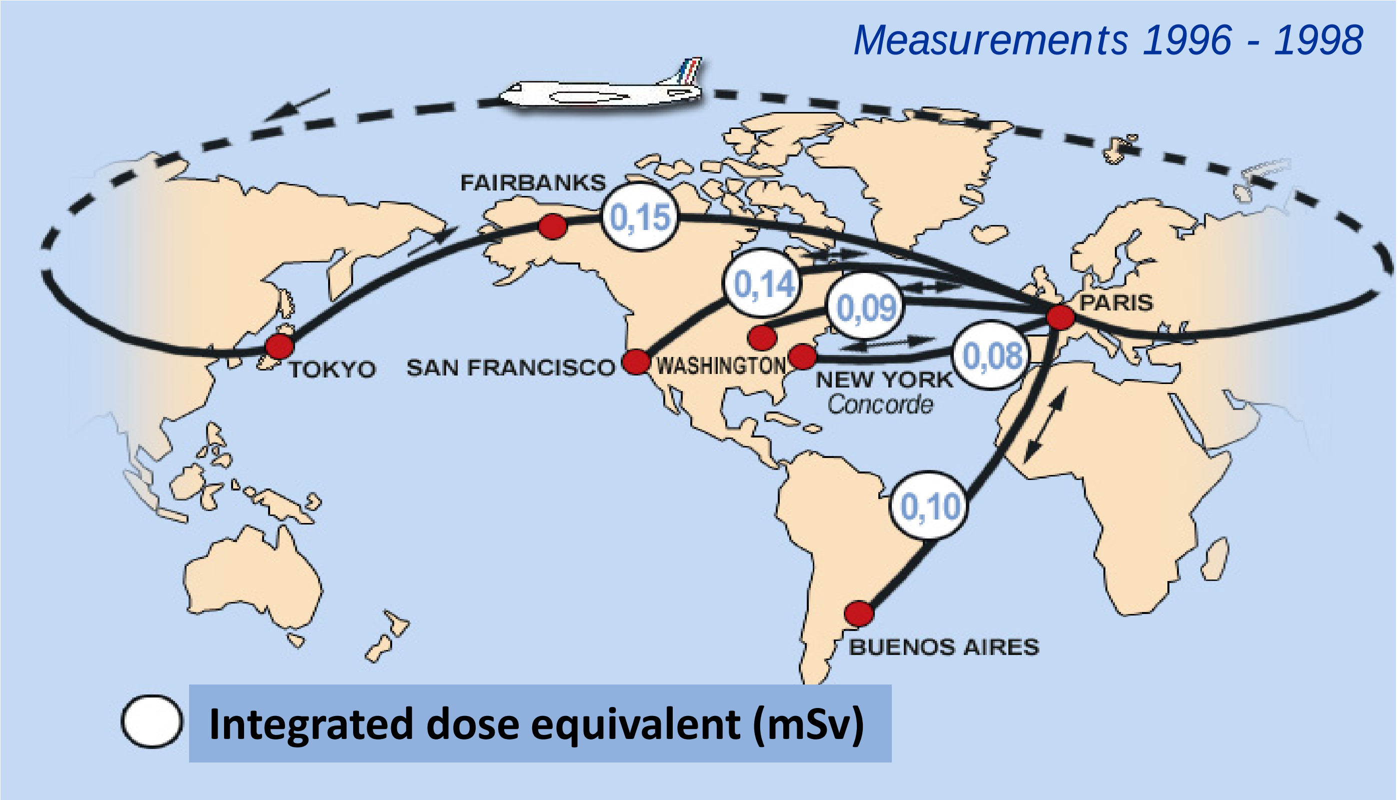
Contribution of the different components to the dose for various flights



'igure II.5 Relative contribution to effective dose, *E*, for various destinations near solar maximum condition (1991) for 37000 ft flight altitude as calculated with EPCARDv.3.2.

EURADOS report, 2004

Dose for typical flights



GCR - Measurement comparison

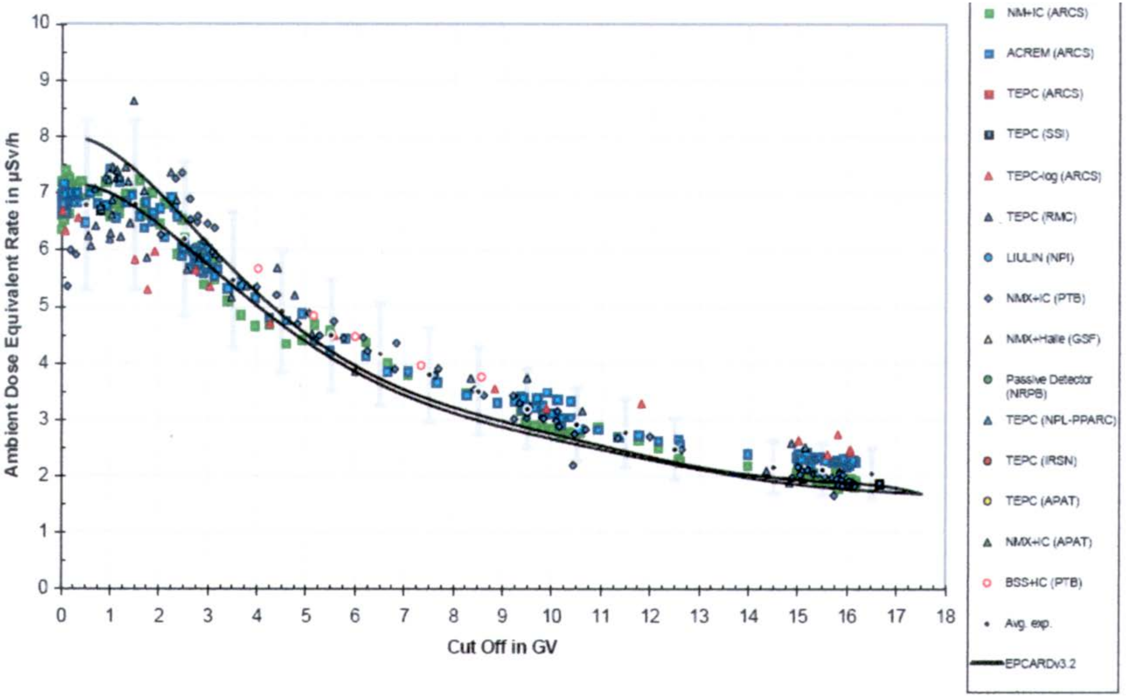
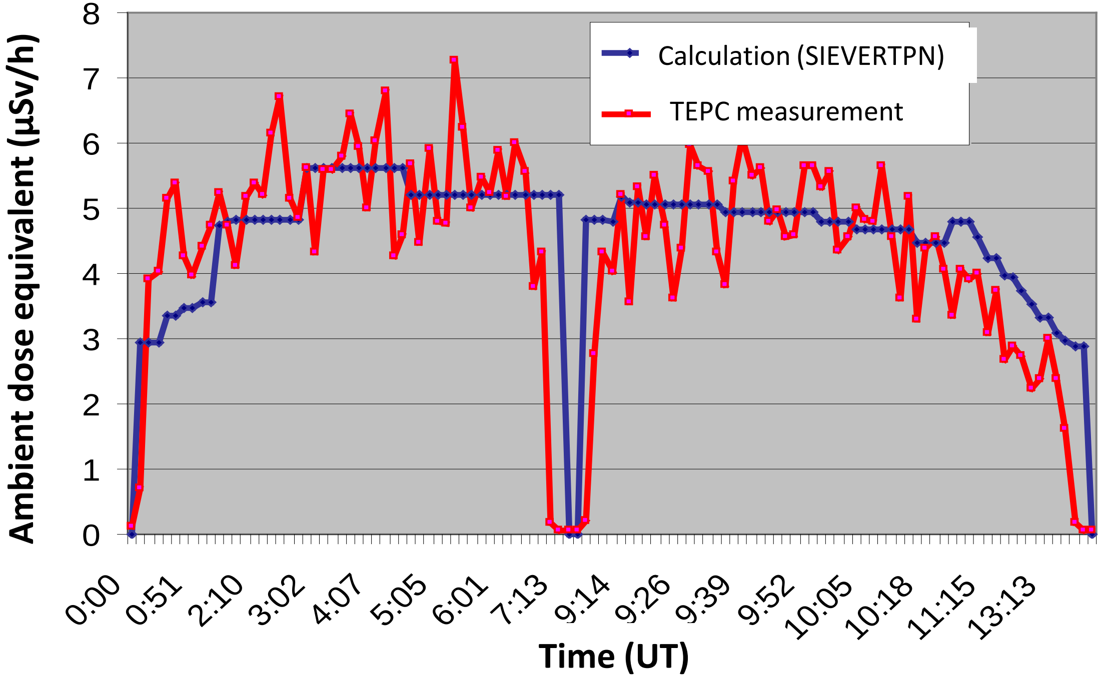


Figure III. 50 Ambient dose equivalent rate dH*(10)/dt vs. vertical cut off rigidity rc between May 1992 and May 2003 for standard barometric altitude 11277 m (FL 370) and for solar deceleration potential in the range of 470 MV - 610 MV.

EURADOS report, 2004

GCR – validation of calculation by measurement



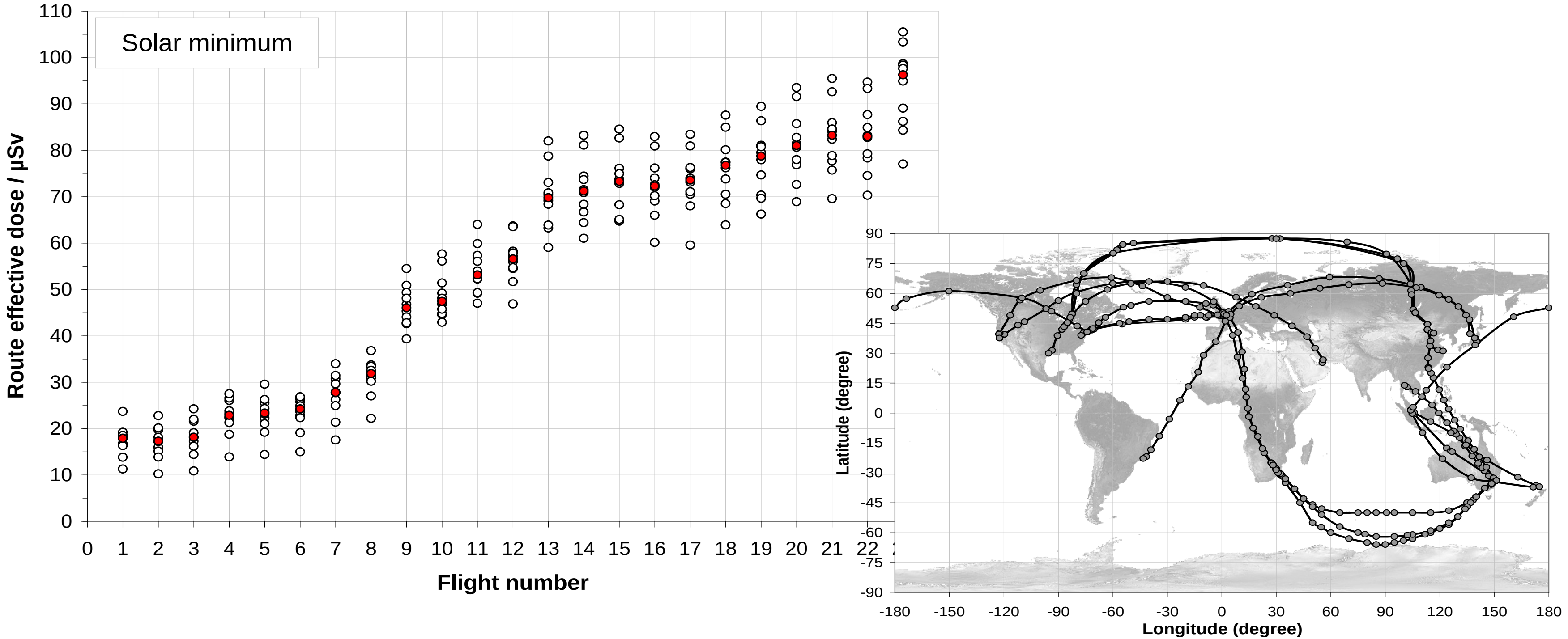
Integrated value *(round trip)*

Measurement : 120±11 µSv

Calculation :* 126 µSv

** Made with SIEVERTPN using EPCARD as GCR model (www.sievert-system.org)*

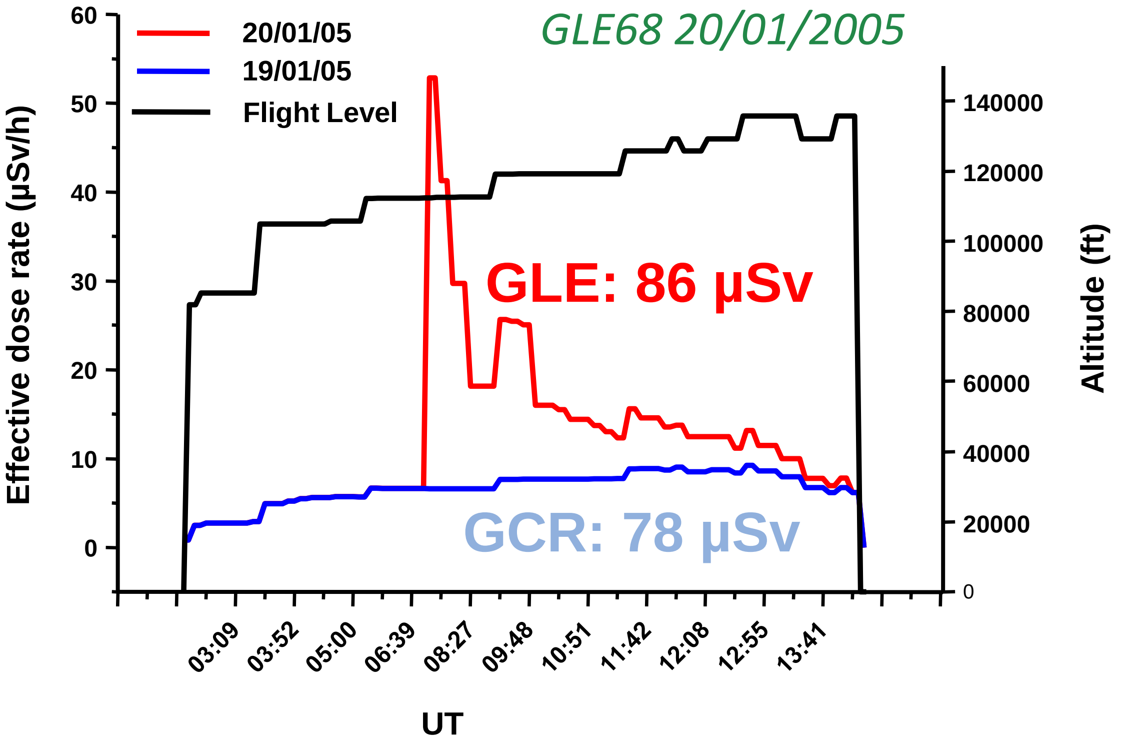
GCR - Comparison of different models

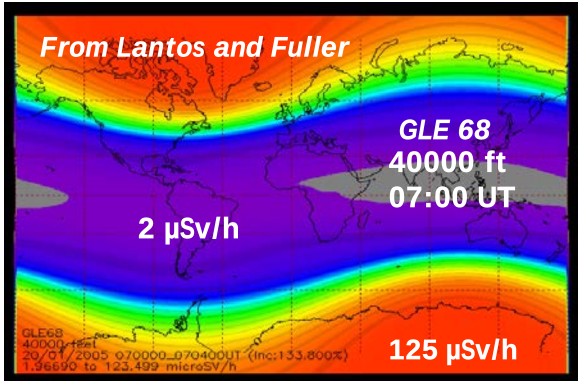


Anonymous comparison of the total effective dose *E* for different mid- and long-haul flights due to galactic cosmic radiation, during solar minimum conditions. The results are calculated using the AVIDOS 1.0, CARI-6M, EPCARD.Net 5.4.1, IASON-FREE 1.3.0, JISCARD EX, PANDOCA, PCAIRE (scientific version), PLANETOCOSMICS 2.0 (Bern model), QARM 1.0, and SIEVERT 1.0 computer codes. The median is marked with red circles.

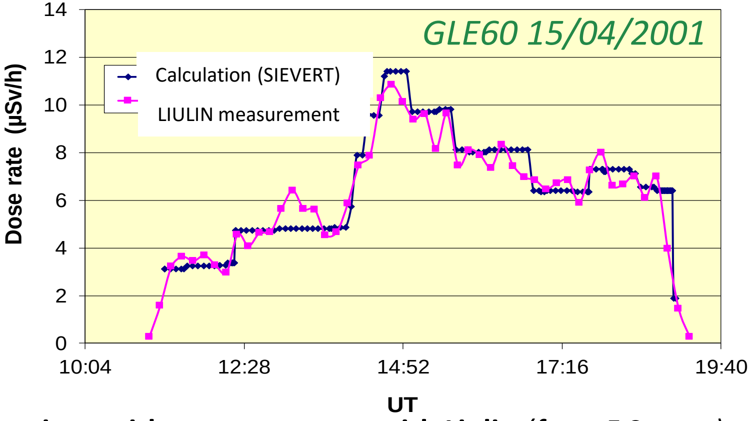
EURADOS report, 2012

GLE : calculation with SIEVERTPN (EPCARD + Sigle models)





Dose rate map using the Sigle model



Comparison with measurements with Liulin *(from F Spurny)*

How characterise and calibrate devices?

- Main contributions to the radiation field at aviation altitudes are neutrons *(few hundred keV up to a few GeV)*, protons *(few tens of MeV to a few GeV)*, electrons, positrons and photons (few MeV to a few GeV)

- ISO reference radiations do not fully cover the energy range of photons, neutrons and electrons

- Thus additional calibration fields are required, including, for some devices, proton radiation fields. Non ISO fields can be used with a traceable technique to measure the particle fluence and convert it to ambient dose equivalent by applying fluence to dose conversion factors ☞*Example*

- Specific standards have been developed: ISO 20785 series on *Dosimetry for exposures to cosmic radiation in civilian aircraft — Part 1: Conceptual basis for measurements; Part 2: Characterization of instrument response*; *Part 3: Measurements at aviation altitudes* and *Part 4:Validation of Codes* ☞*Example*

Radiation fields recommended for calibrations and intercomparisons *(from ISO 20785-2)*

Neutron

- Radionuclide and mono-energetic neutron fields with $E < 20$ MeV: *covered ISO 8529 series*
- High-energy neutron fields $E > 20$ MeV: *no ISO standards. Various facilities providing neutrons with energies up to few hundreds MeV (UCL, iThemba, TSL, TIARA, RRC…)*

Charged-particles

- Various facilities (> 20 facilities worldwide) providing protons and heavy particles up to few GeV

Simulated workplace fields

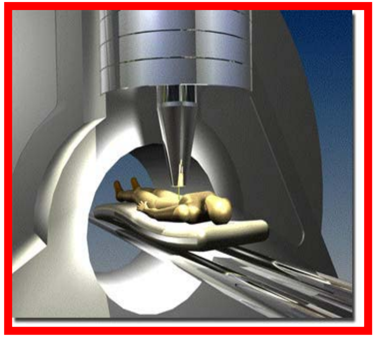
- CERF (CERN-EU high-energy Reference Field) facility. Fields are created by high-energy protons and pions 120/ 205 GeV/c) on a copper target surrounded by iron or concrete shieldings simulating atmosphere (80 cm concrete ~ 10-15 km altitudes)

Natural fields

- Stations on mountains where fields are characterised could be used like *Chacaltaya (Bolivia), Jungfraujoch (Switzerland), Zugspitze (Germany), Cervino and others (Italy), Moussala (Bulgaria), Lomnický štít (Slovakia), Norikura and Fuji (Japan)…*

Example of high energy neutron spectrometer: the HERMEIS system

- **Bonner sphere system**
  11 PEHD spheres + 3 spheres with metal shell
- **Neutron energy range**
  < 20 MeV up to GeV
- **Application**
  - High energy facilities
  - Cosmic Neutron at altitude



Courtesy of V Lacoste, IRSN

Practical application: calibration and CR monitoring onboard aircrafts

Objective

- Operational GLE management
- Experimental data for validation GLE mode**ls**

Main challenges

- Set up dosimeters on a large number of aircrafts (~ 30)
- Perform continuous measurements
- Select « cheap » dosimeters easy to operate
- Define a specific calibration procedure
- Operate the dosimeters (data collection, battery change,…)
- Provide information in case of GLE in a short time (few days)

Courtesy of F Trompier, IRSN

« Calibration » approach

- "Onboard calibration" during dedicated flights
- TEPC measurements are the reference
- Dosimeters used : γ/n APDs + Si-Spectrometer

	γ/Low LET	n/high LET
CDG-SFO	0.68(4%)	9.2 (21%)
SFO-CDG	0.61 (3%)	9.5 (14%)
CDG-KIX	0.57 (5%)	8.6 (27%)
KIX-CDG	0.59 (5%)	8.9 (23%)
Average	0.61 (8%)	9.1 (4%)

Calibration factor for EPDN2's (5 & 12)

Courtesy of F Trompier, IRSN

HAWK TEPC (Far West)

EPDN2 (Thermo electron)

Liulin (Sofia univ.)

	D(Si)/H*(10)
CERF	18
CDG-SFO-CDG	15.8

Calibration factor for Liulin

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DOSIMETRY IN SPACE

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Context and challenges

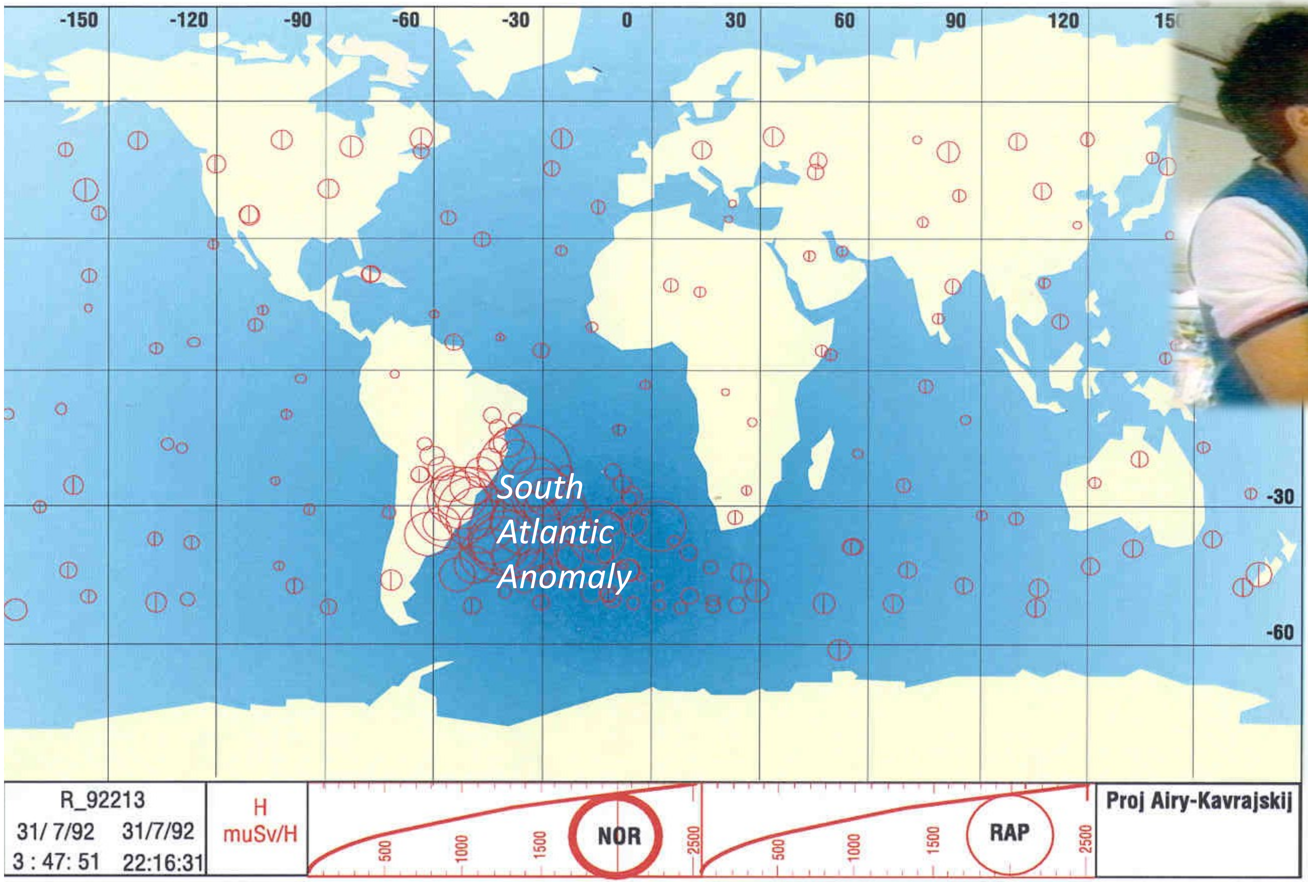
- In space, the protection is lower and the exposure higher than on Earth:
  - *Aboard ISS*: no atmosphere but Hearth magnetic field
  - *Moon:* no magnetic field and no atmosphere
  - *Mars:* no magnetic field and thin atmosphere *(20 g.cm^{-2} of CO_2 (1/50 of Earth)*
- The effect of a SPE may be (very) important but is all the more attenuated as the protection is important
- The field components and their characteristics may vary strongly depending on the shielding *(spacecraft, buildings, in free space or at the surface)*
- Dosimetry is made by measurements and no models:
  - Occupational exposure for space crews can be made with personnel dosimeters, *like TLDs for low LET and track etched detectors for heavy ions and neutrons*
  - Area monitoring outside or inside a spacecraft or a building *(control and hence for warning in cases of SPE)*. Measurements of particle types, fluences and microdosimetric quantities and absorbed doses, using detectors in assemblies of various sizes, both integral and differential *(with respect to time, or LET, or energy, or direction, as appropriate)*

Exposure in space for GCR

Localisation	Earth *(sea level)*	ISS	Space craft *(travel)*	Mars *(ground)*
Ambiant dose equivalent* *(mSv/day)*	**0,001**	**0,7**	**1,8**	**0,6**
Shielding *($g.cm^{-2}$)*	**1000** *(air)*	**15** *(Al)*	**15** *(Al)*	**20** *(CO_2)*

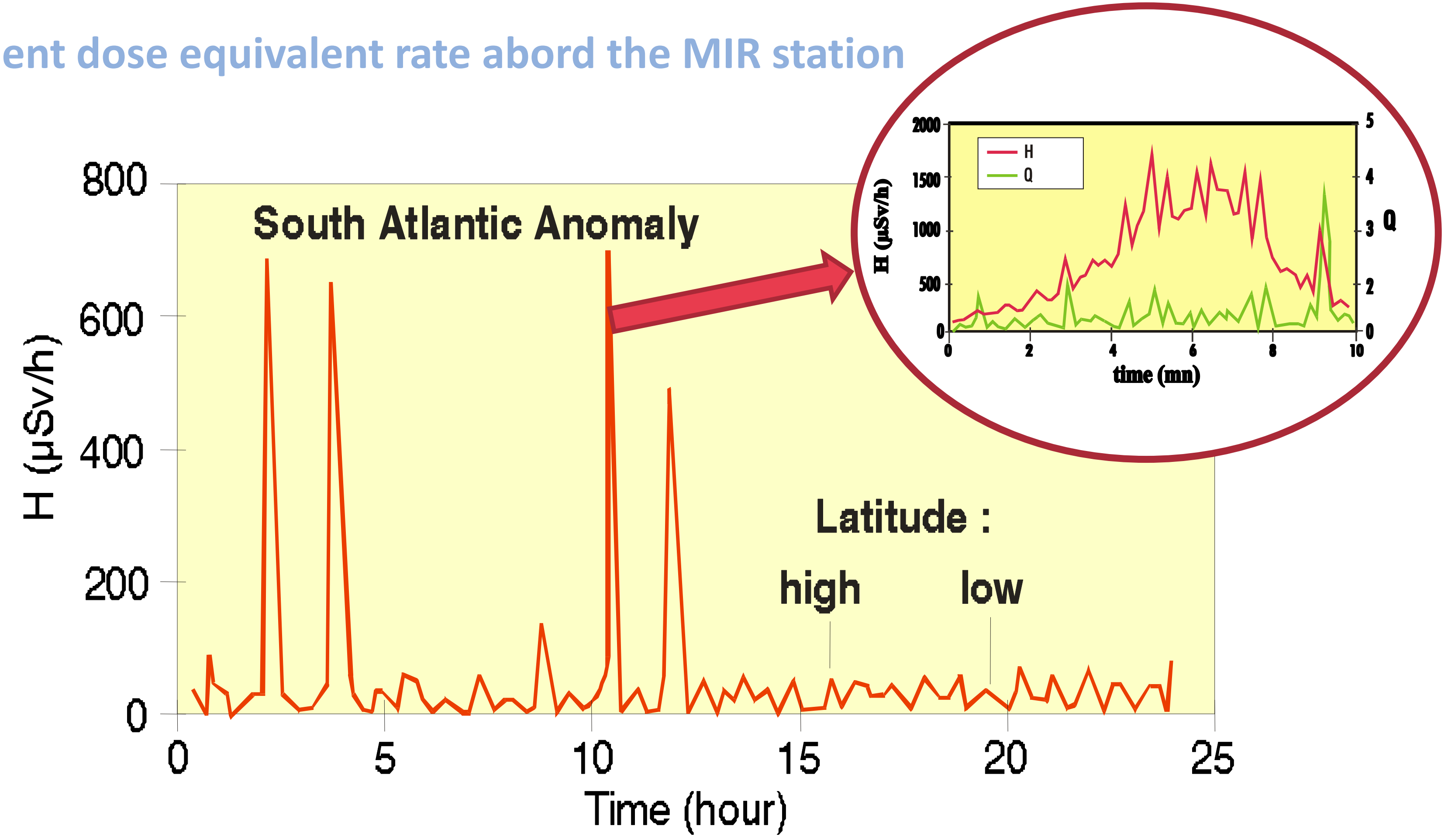
** Without solar particle event*

Ambient dose equivalent rate abord the MIR station (GCR)

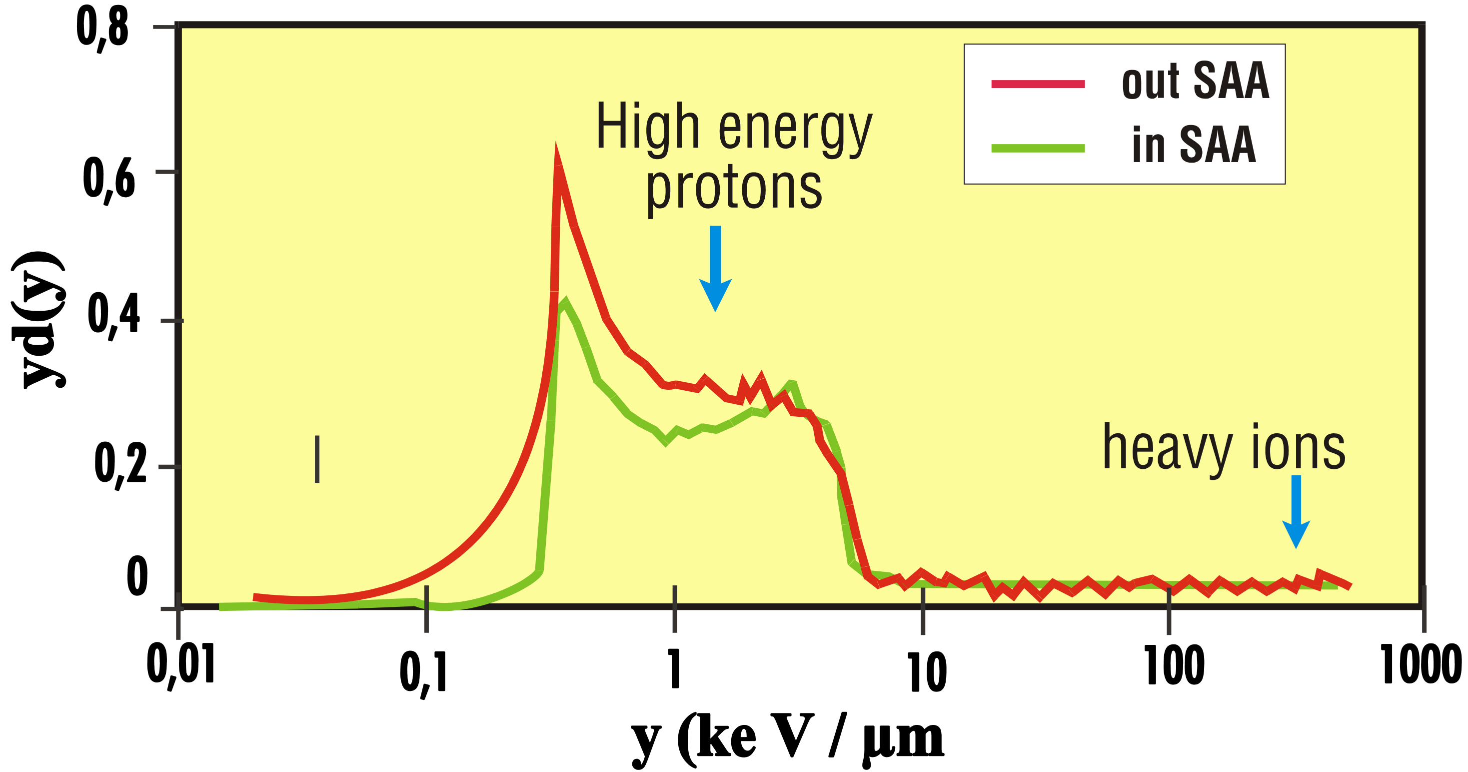


Measurements with a TEPC (NAUSICAA)

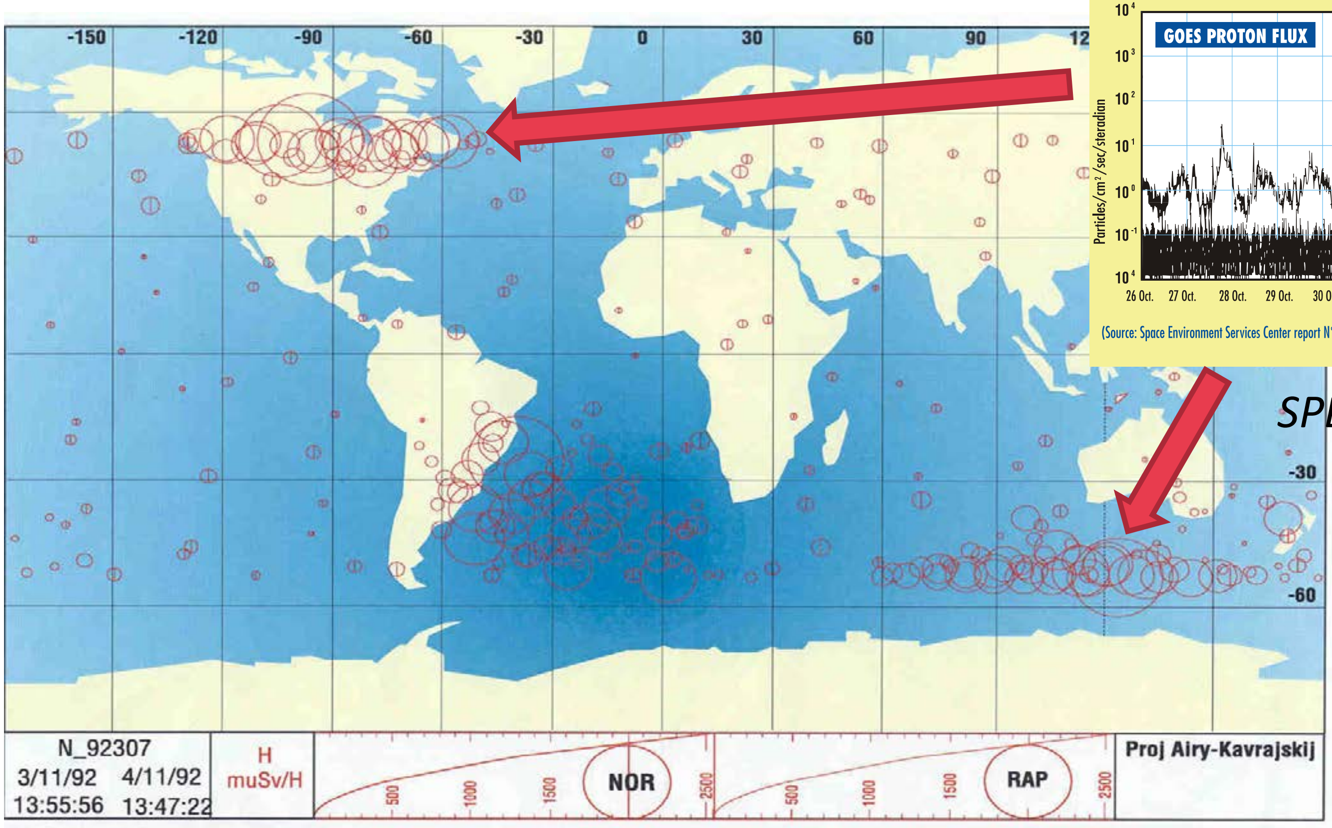
Ambient dose equivalent rate abord the MIR station

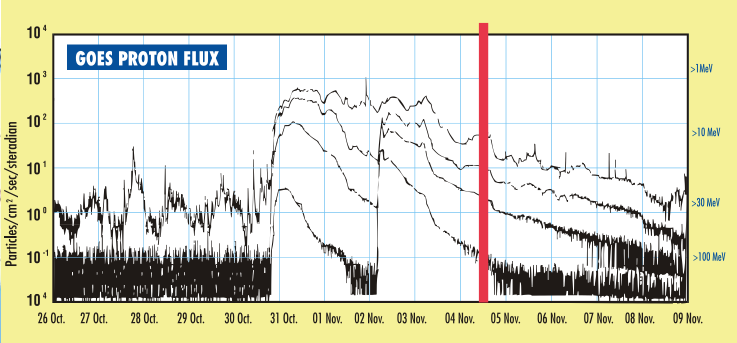


Dose distribution as a function of LET



Ambient dose equivalent rate abord the MIR station (GCR + SPE)





(Source: Space Environment Services Center report N°896 - 897 1992)

SPE occurred on 31/09/1992

Lessons Learned from the Radiation Measurements of the Mars Science Lab Radiation Assessment Detector (MSL-RAD)

Guenther Reitz

On behalf of the MSL-RAD Science Team

Radiation Biology Department, Institute of Aerospace Medicine,

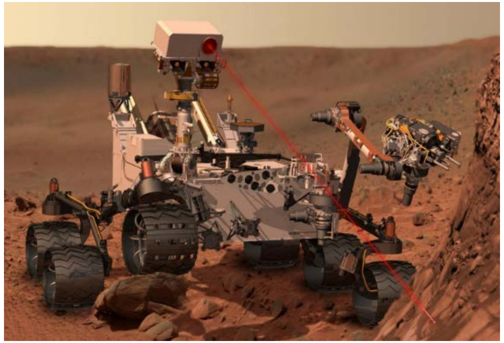
German Aerospace Center (DLR), Köln, Germany

Nuclear Physics Institute of the CAS, Department of Radiation Dosimetry, Řež, Czech Republic

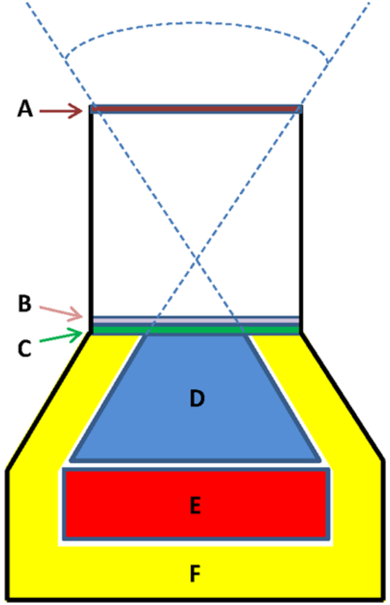
Knowledge for Tomorrow

A Brief History

- RAD was selected for MSL in 2004.
- Moderately shielded environments are highly pertinent to human flight.
  - ~ 16 g cm-2 spacecraft shielding during cruise
  - ~ 20 g cm^{-2} CO_2 shielding on Mars
- MSL was launched Nov 26, 2011 and landed Aug 6, 2012 on Mars
- RAD operated during the entire cruise and is close to celebrate three Martian years of operations
- Sol = Martian day = 1.02 Earth day
- 687 Earth days = 1 Mars year



RAD Sensor Head Schematics & Measurement Capabilities

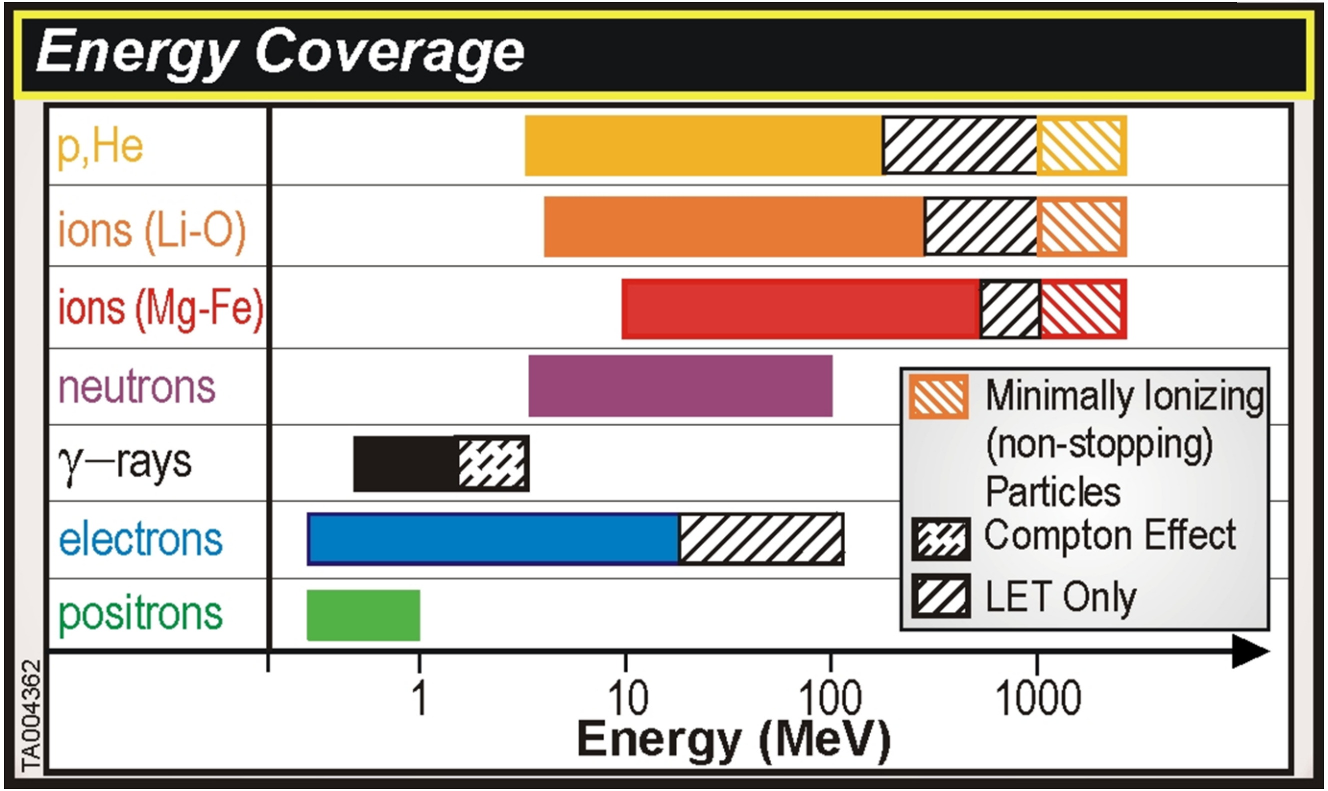


- 3-element silicon particle telescope (A, B, C).
- CsI scintillator (D).

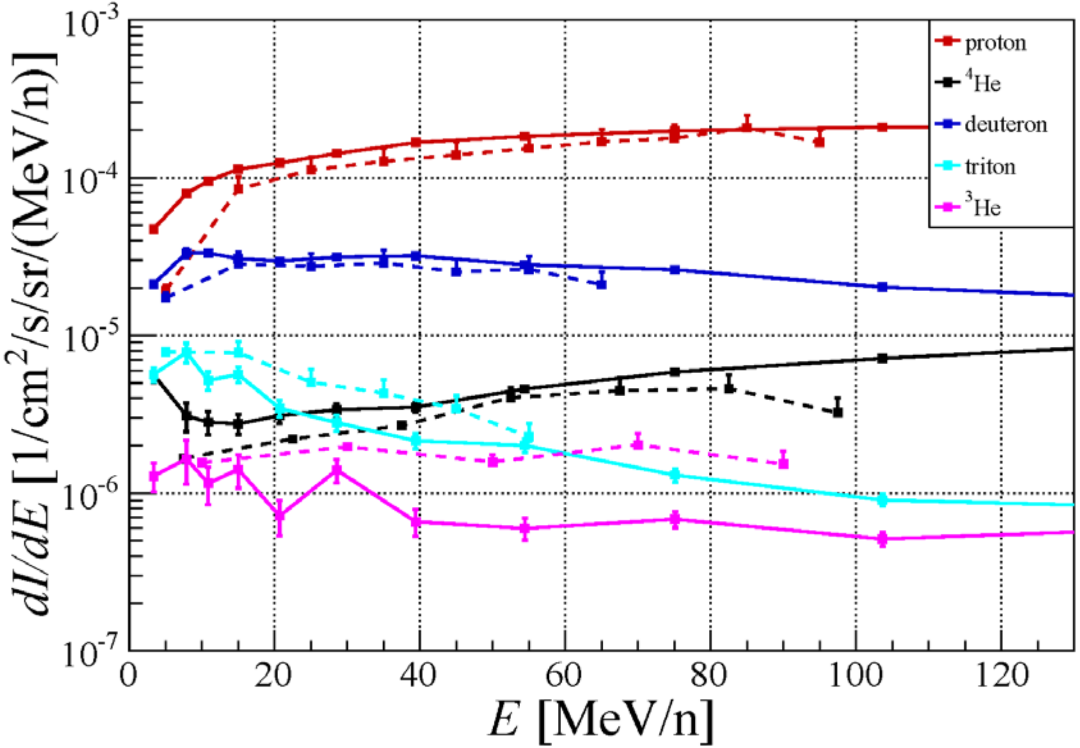
  for γ-ray detection; stops protons and 4 He up to ~ 95 MeV/nucl
- Plastic scintillators (E, F).

  F enables neutral particle detection in D (ɣ's) and E (neutrons).

RAD Measurement Capability



MSL-ground, low *Z* - 20 g/cm²
(no shielding from Rover included)



solid lines: GEANT4

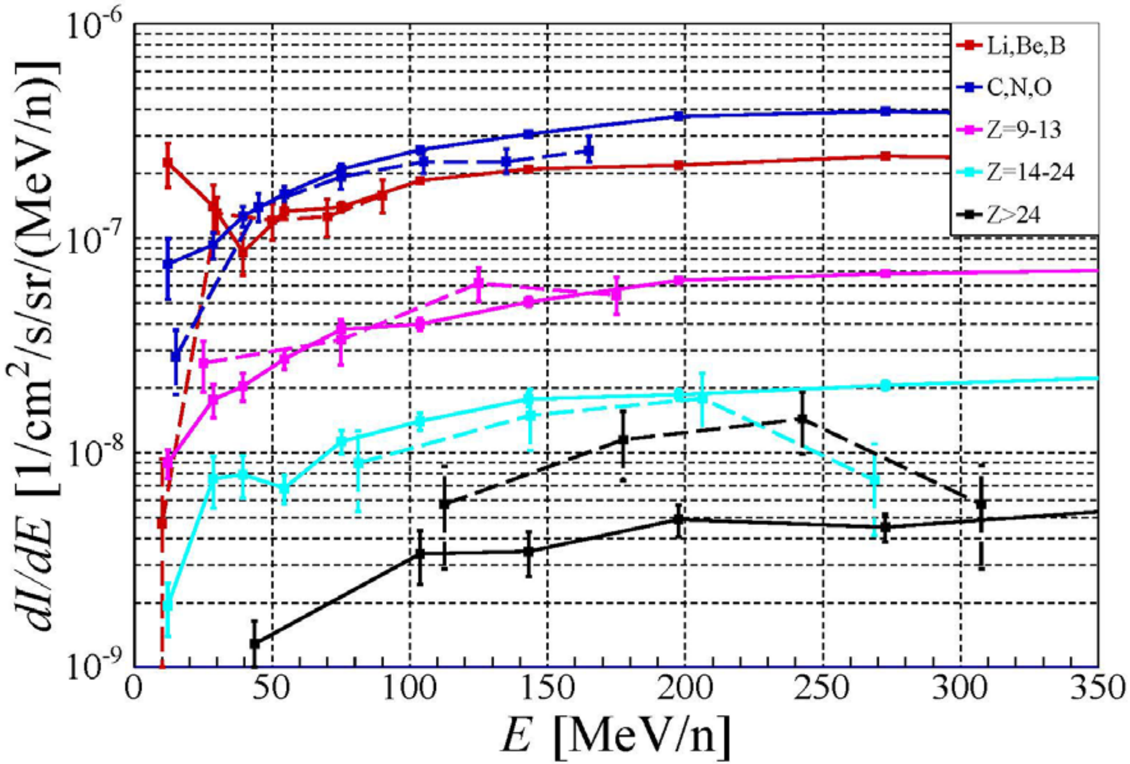
dashed lines:

Ehresmann et al.,

JGR Planets 119, 2014

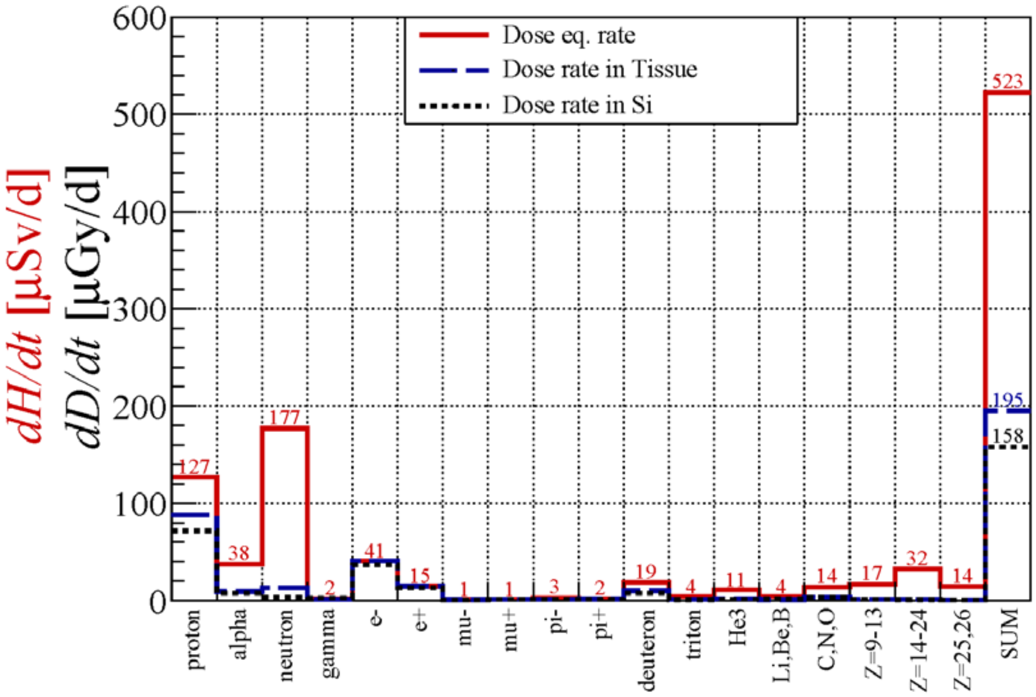
MSL-ground, high *Z*- 20 g/cm^2

(no shielding from Rover included)



solid lines: GEANT4
dashed lines:
Ehresmann et al., JGR Planets 119, 2014

Absorbed Dose Rate and Dose Equivalent Rate on the Surface of Mars



MSL-RAD: 0.21±0.04 mGy/d; 0.64±0.12 mSv/d, Q=3.05±0.3

Radiation Environment Measured by MSL/RAD during cruise and on the Mars surface(GCR only), Hassler et.al, Science 2013

RAD Measurement	Cruise	Mars Surface	Units
Charged Particle Flux (A2*B)	1.43 +/- 0.03	0.64+/- 0.06	$cm^{-2}\ s^{-1}\ sr^{-1}$
Fluence Rate (B)	3.87 +/- 0.34	1.84+/- 0.34	$cm^{-2}\ s^{-1}$
Dose Rate	0.48 +/- 0.08	0.21 +/- 0.04	mGy/day
Avg. Quality Factor <Q>	3.82 +/- 0.30	3.05 +/- 0.30	(dimensionless)
Dose Equivalent Rate	**1.84 +/-0.30**	**0.64 +/- 0.12**	**mSv/day**

Preliminary Dose Estimates for NASA "Design Reference" Mission

Mission Phase	Dose Equivalent/ Effective Dose (Sv)	Notes
Cruise to Mars (180 days)	~ 0.33 / 0.22	near Solar Max
Mars Surface Mission (600 days)	~ 0.38 / 0.24	Thin habitat shielding
Mars Surface Mission (300 days)	~ 0.19 / 0.12	Thin habitat shielding
Return to Earth (180 days)	~ 0.33 / 0.22	near Solar Max
Total Mission Dose Equivalent (300 days on Mars)	**~ 0.85 / 0.56**	300 days
Total Mission Dose Equivalent (600 days on Mars)	**~ 1.04 / 0.68**	600 days

The Astronaut Career Limits vary by Space Agency. NASA Astronaut Career Limit is fixed at 600 mSv corresponding 3% excess risk of exposure-induced death (REID) for a 35 y female

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CONCLUSION

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Conclusion: *specificity of the exposure to CR and its assessment*

- The cosmic radiation is a "high energy & complex field"
  - *At aviation altitude and on Earth:* strong attenuation by atmosphere & filtering by magnetic field

  ➡ GCR (secondaries) + sporadic Ground Level Events (GLE)

  - *In space:* small attenuation by atmosphere/spacecraft shielding & no magnetic field

  ➡ GCR + Solar Particles Events (SPE)

- Typical exposure levels: ~0,1 µSv/h on *Earth*; 1-10 µSv/h at *aviation altitude*; 30-70 µSv/h *in space*

- Dosimetry approach
  - *In aviation:* calculation using models for occupational exposure and measurements mainly for their validation
  - *In space:* measurements with appropriate systems for personal dosimetry and area monitoring

Conclusion: *a challenge for calibration and metrology*

- Main contributions to the radiation field are neutrons *(few hundred keV up to a few GeV)*, protons *(few tens of MeV to a few GeV)*, electrons, positrons and photons (few MeV to a few GeV) *at aviation altitudes* + heavy ions *in space*

- ISO reference radiations do not fully cover the energy range for photons, neutrons and electrons

- Thus additional "calibration" fields are required, including protons and heavier ions fields. Non ISO fields can be used with a traceable technique to measure the particle fluence and convert it to ambient dose equivalent by applying fluence to dose conversion factors

- Specific approaches are defined for characterisation and calibration of instruments

- For dosimetry at aviation altitude, specific standards have been developed: ISO 20785 series on *Dosimetry for exposures to cosmic radiation in civilian aircraft*

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