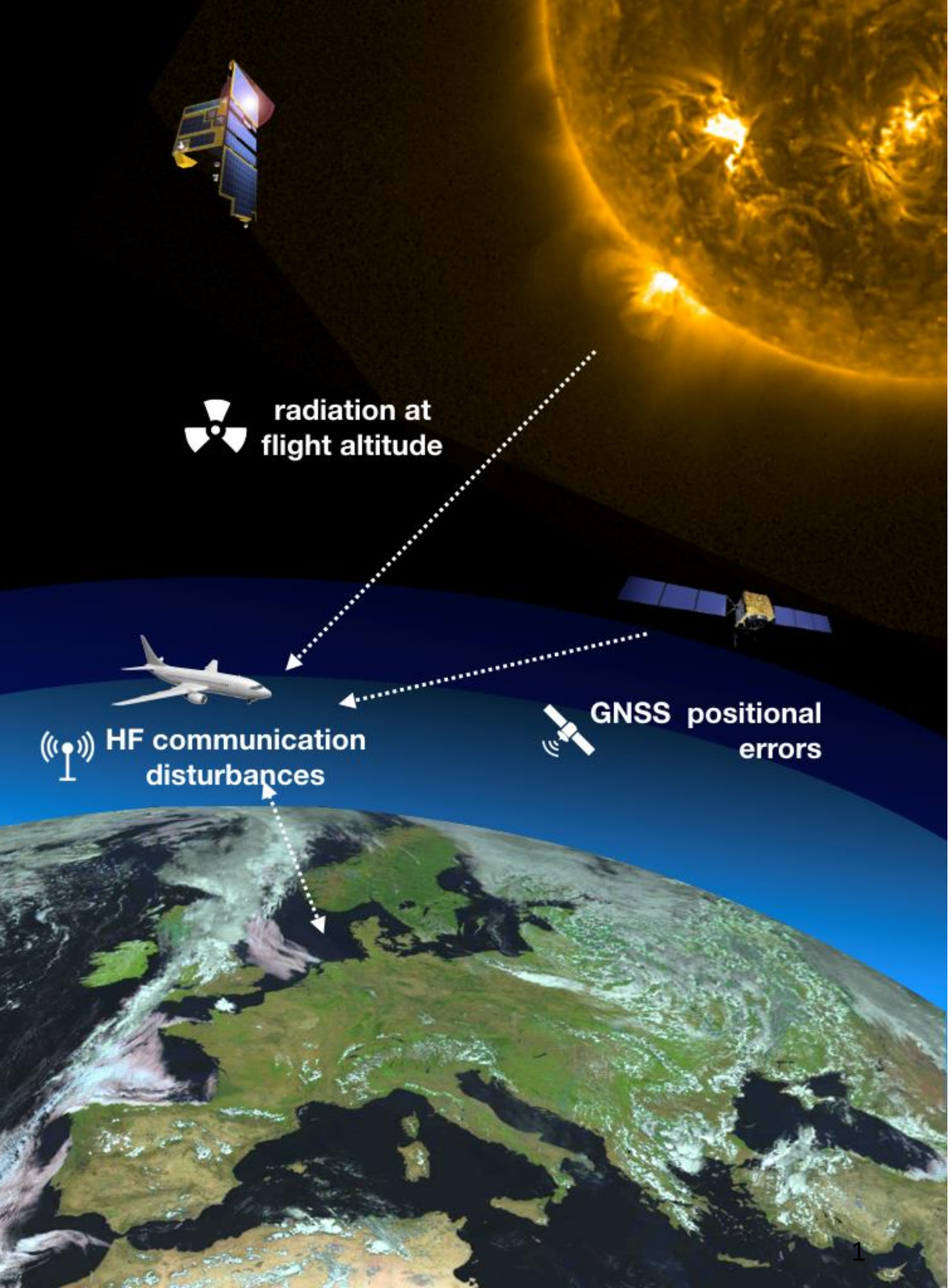


Space Weather impacts on Aviation

PECASUS advisories for ICAO

Course by the
Solar-Terrestrial Centre of Excellence

March 2024

Atmospheric radiation

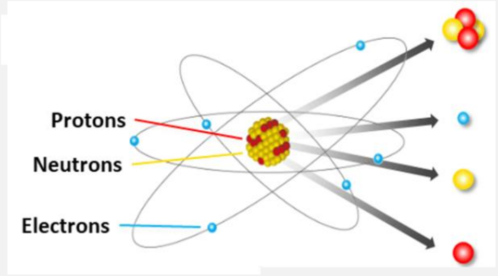
E. De Donder (erwin.dedonder@aeronomie.be)

- Sources
- Effects
- Mitigation measures

(PARTICULATE RADIATION)

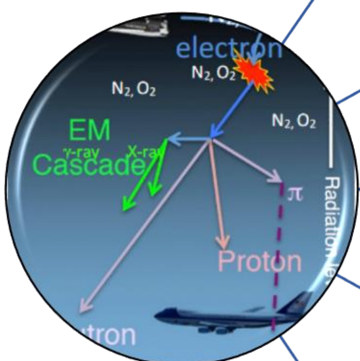
→ Energy transmitted by fast-moving atomic or sub-atomic particles (electrons, protons, neutrons, alpha particles, etc.)

→ Few m/s up to sizable fraction of c



→ <100 keV : plasma

Radiation sources producing ‘Atmospheric radiation’



CR

- Galactic Cosmic Radiation (GCR)
- Solar Energetic Particles (SEPs)

(ionising radiation)

EMIC

- Electromagnetic Ion Cyclotron waves
- Precipitation relativistic electrons from radiation belt
  → |43°-67°| (magn.),
  → > GCR background
  → Ongoing research!!

(ionising radiation)

UV

- UV-A (315-400 nm) exposure in cockpit
- Windshield UV-A attenuation

(non-ionising radiation)

TGR

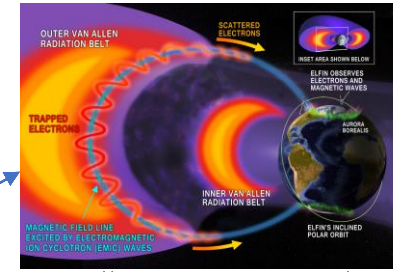
- Terrestrial Gamma-ray Flashes
- Thunderstorms: milliseconds, E < 40 MeV, rather X-rays, equatorial region

(ionising radiation)

Cargo

- Radio-active material: research, commercial, radiopharmaceutical

(ionising radiation)



(https://spaceweatherarchive.com/2018/09/20/student-built-space-weather-satellite-targets-killer-electrons/)

Space component

Primary cosmic radiation: GCR and SEP

Galactic Cosmic Radiation (GCR)

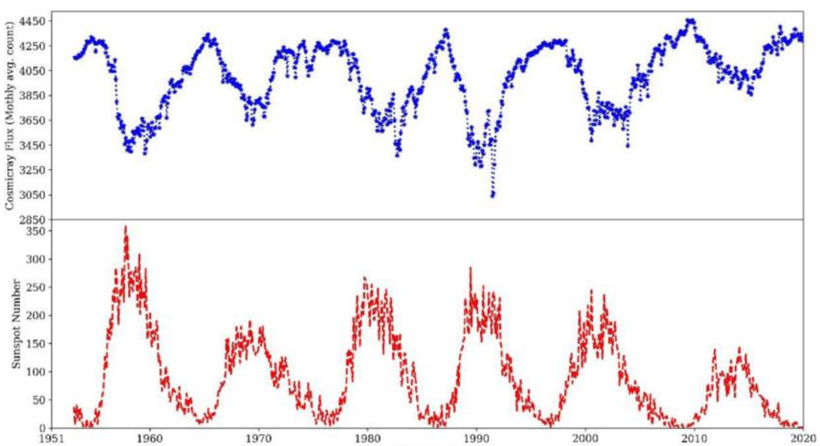
- Origin outside solar system (SNe, AGN, …)
- Isotropic (equally from all directions)
- Permanent background radiation throughout solar system
- High energetic fully ionized atomic nuclei (89% p^+, 10% He, 1% Z>2)
- Modulated by sun's magnetic field (IMF): min. at solar max – max. at solar min. (~factor 2-3)

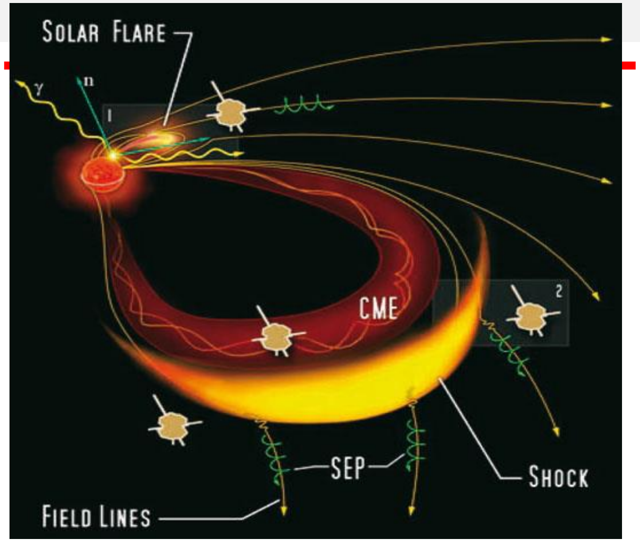
→ ~8 μSv/h @12 km

Solar Energetic Particles (SEP)

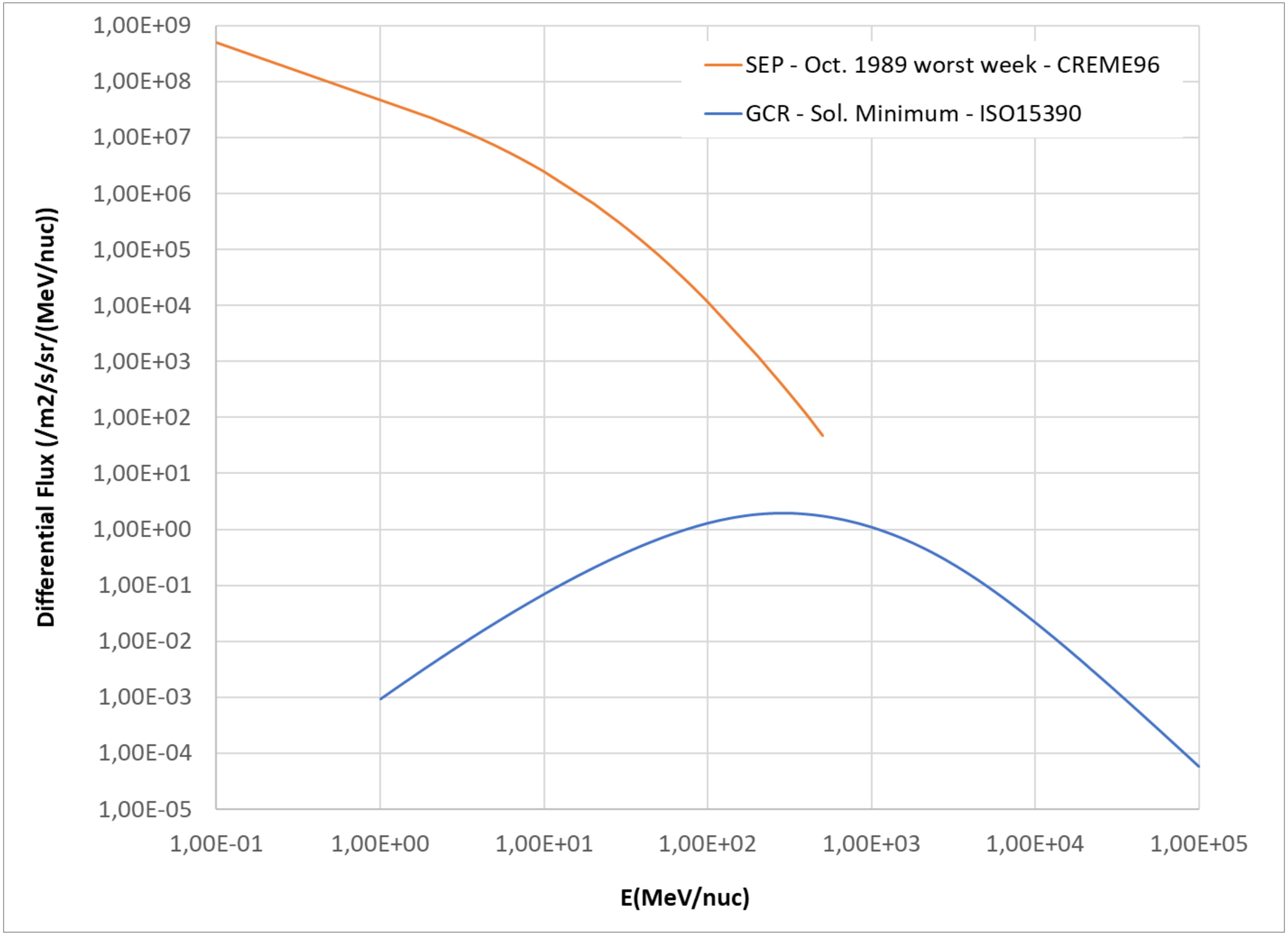
- Origin in solar flares and Coronal Mass Ejections (CME's)
- ~15-20 min to reach Earth
- Sporadic
- Similar composition as GCR with mainly protons
- Can produce Forbush Decreases (FD) and Ground Level Enhancements (GLE) on the ground

→ ~3000 μSv/h @12 km





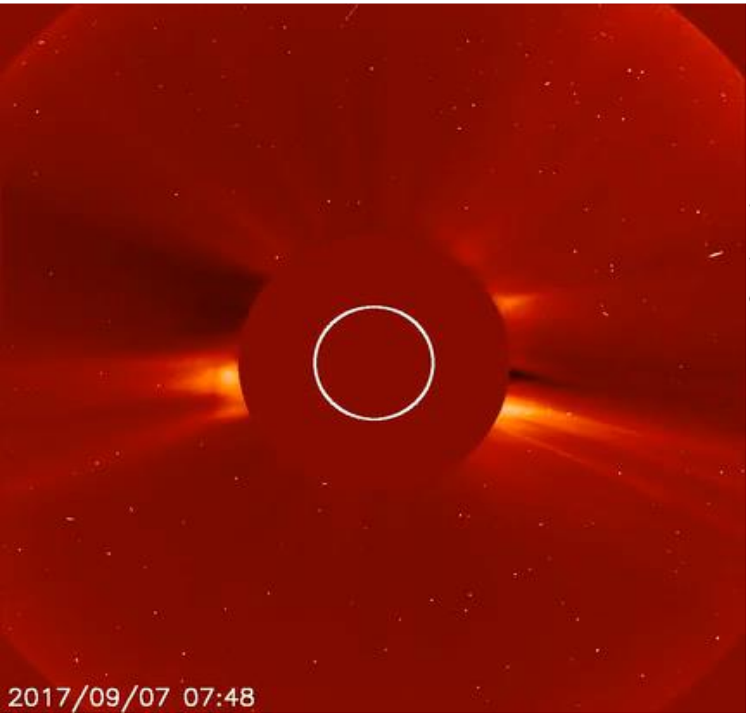
SEP vs. GCR energy flux spectrum at 1 AU



SPENVIS simulation (https://www.spenvis.oma.be)

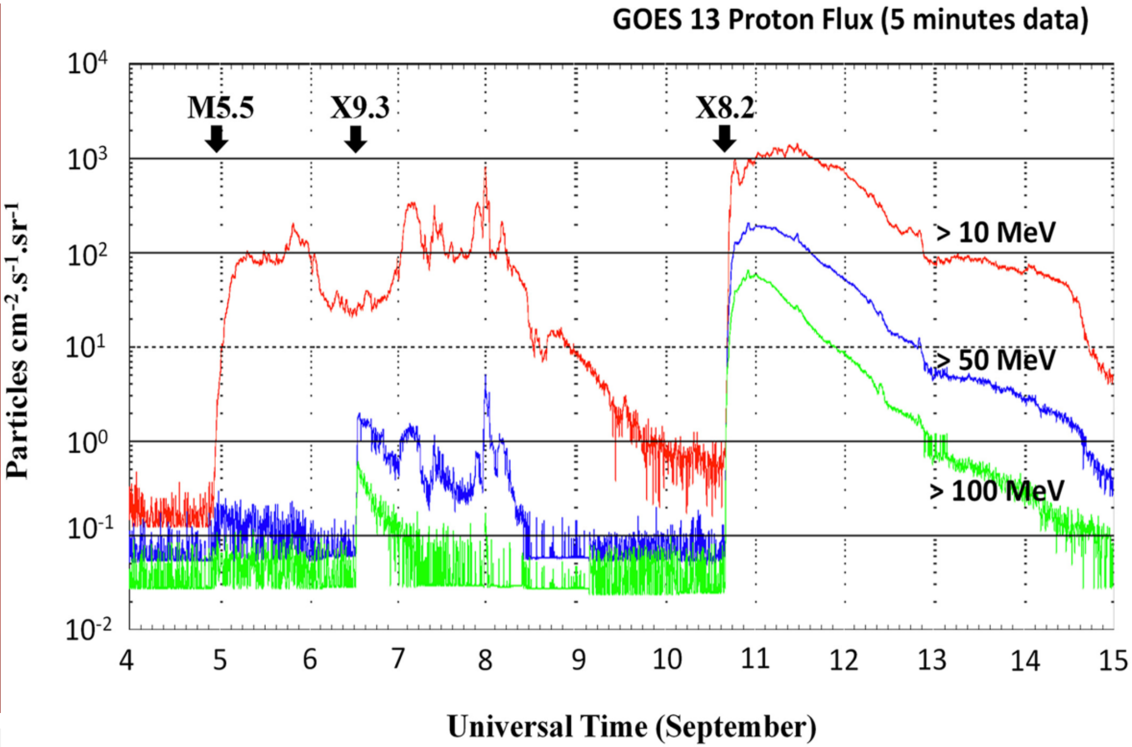
SEP events detection in space

Example: September 2017 event(s)



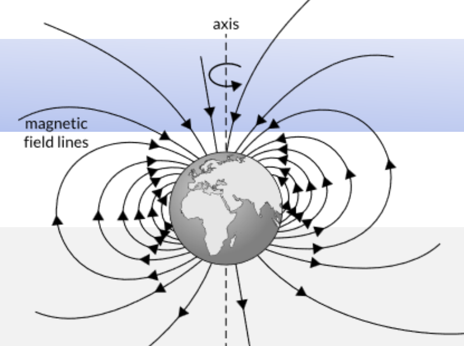
SOHO/LASCO coronograph @ L1 (~$1.5 \cdot 10^6$ km)

(https://www.esa.int/esatv/Videos/2017/09/Solar_events)



GOES-13/EPEAD @ GEO (~$36 \cdot 10^3$ km)

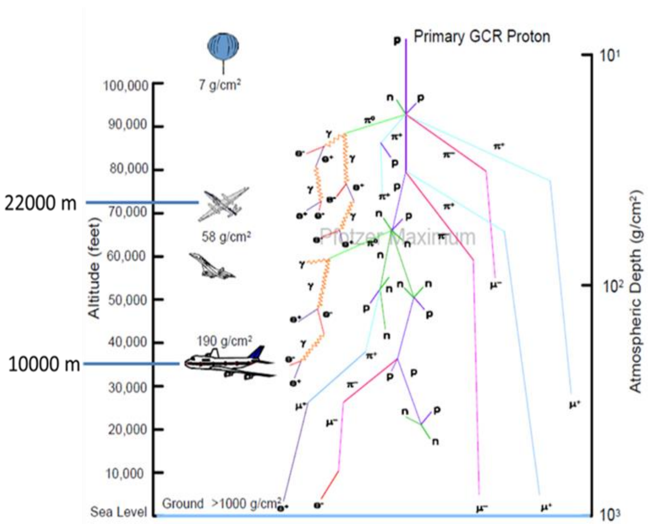
SEP events detection on the ground (1/2)



Primary spectrum is modified by:

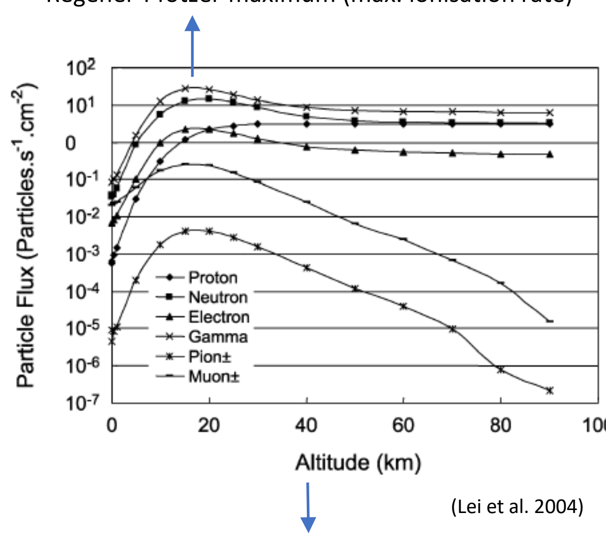
- Earth magnetic field → deflection ("rigidity cut-off" = Rc in GV) → geomagn. lat. dependence
  → (weakened during geomagnetic storm !!)
- Earth atmosphere → nuclear reactions (N_2, O_2) + attenuation → altitude dependence

➔ SEP event must be energetic enough to reach the ground (>200-500 MeV)

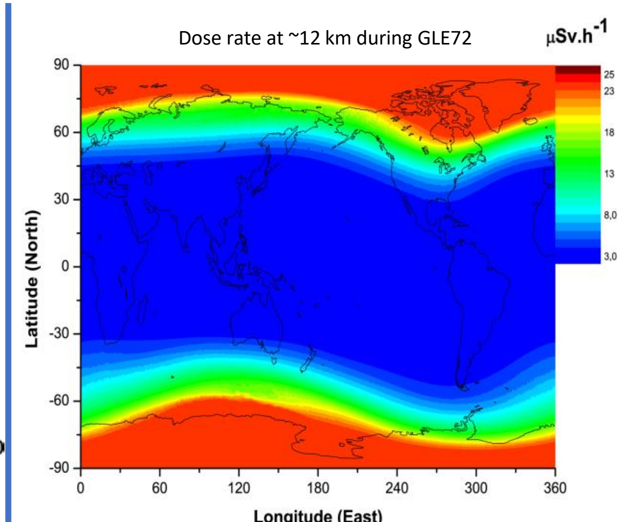


http://physics.okstate.edu/people/faculty-directory/93-pages/540-benton-rpl-studies-in-cosmic-ray-muons

Regener-Pfotzer maximum (max. ionisation rate)



Neutrons have the **highest linear energy transfer (LET)** value

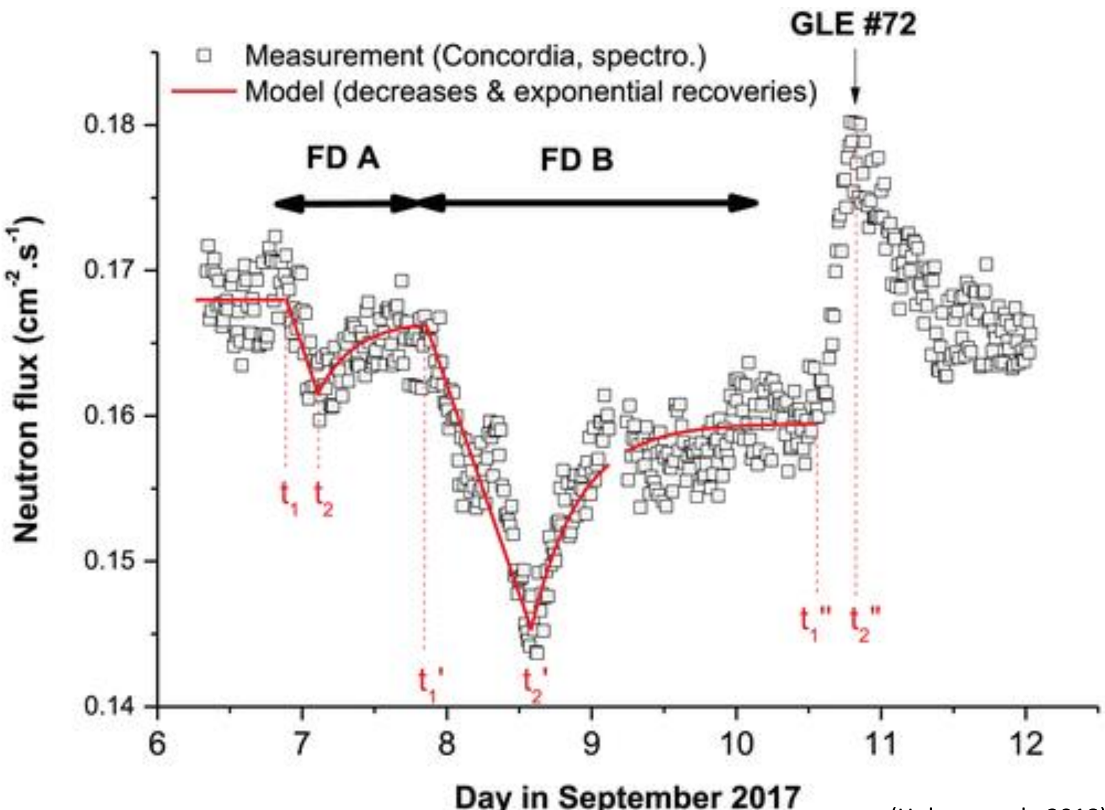


(Mishev&Usoskin, 2018)

(rigidity = momentum/charge)

SEP events detection on the ground (2/2)

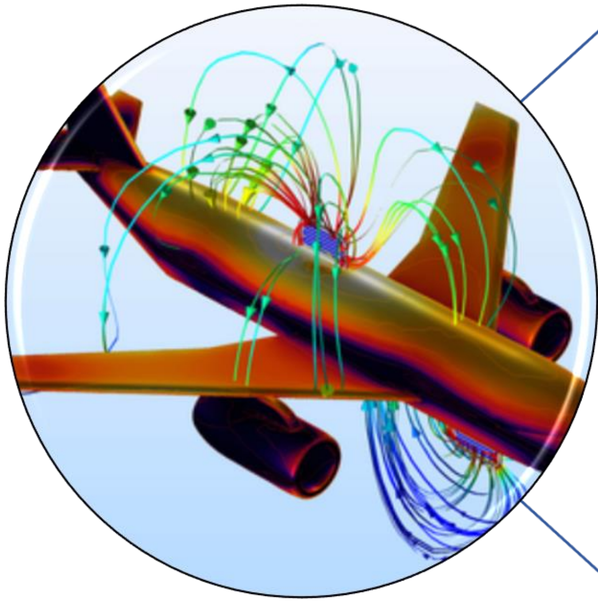
- Forbush decrease → neutron flux dip (GCR ↘)
- Ground level enhancement → neutron flux peak (+ SEP)



Concordia station (Antarctica, +3,233 m)

(Hubert et al., 2018)

Radiation impacts at flight level



HEALTH

- Increased dose rate
- Active Implanted Medical Devices (AIMDs)

AVIONICS

- Single Event Effects (SEE)
  → e.g. Bit flips

HF COMM

- Polar Cap Absorption (PCA)
  → >82° N lat.

Effective Dose

→ Calculated quantity used to assess the probability for radiation induced cancer and other genetic effects

$$E = \sum_{T} w_{T} H_{T} = \sum_{T} w_{T} \sum_{R} w_{R} D_{T,R}$$

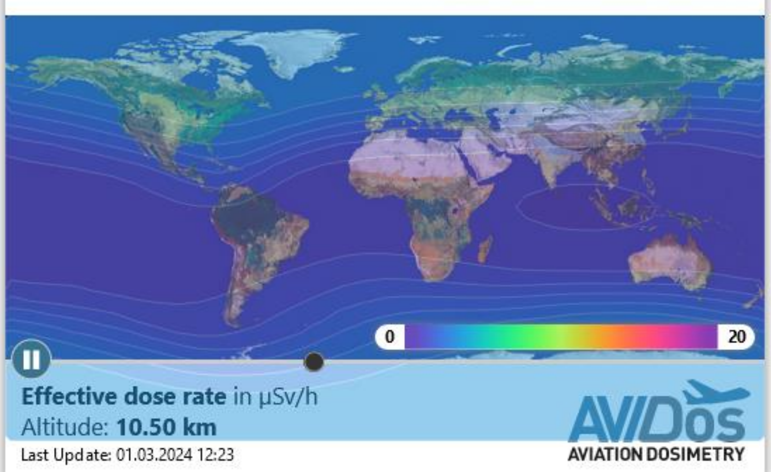
(Sievert = Sv = J/kg)

- w_T: tissue weigthing factor
- w_R: radiation weigthing factor
- $D_{T,R}$: absorbed dose by tissue T due to radiation type R

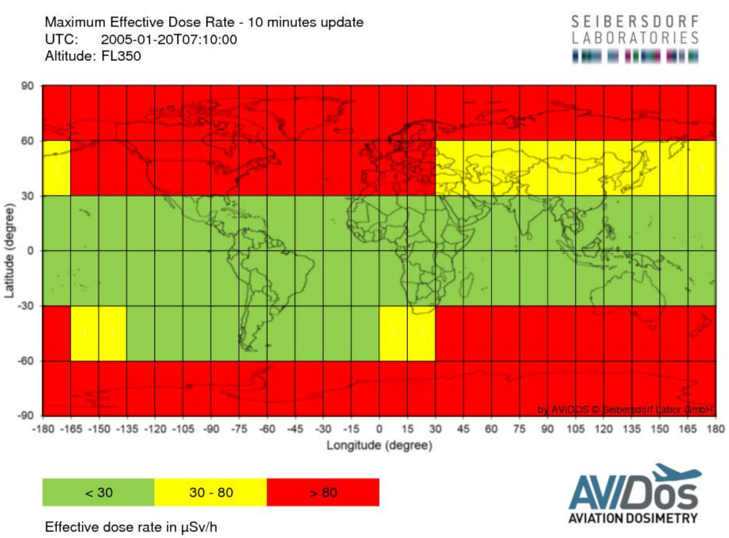
AVIDOS tool (AVIation DOSimetry)

https://avidos.seibersdorf-laboratories.at/esa/map/

SEIBERSDORF LABORATORIES

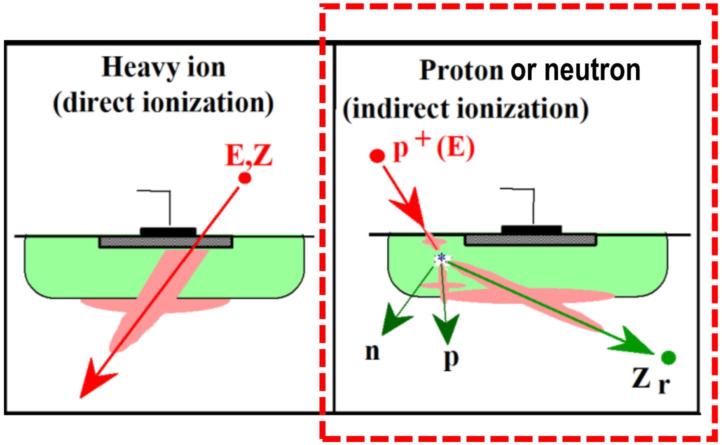


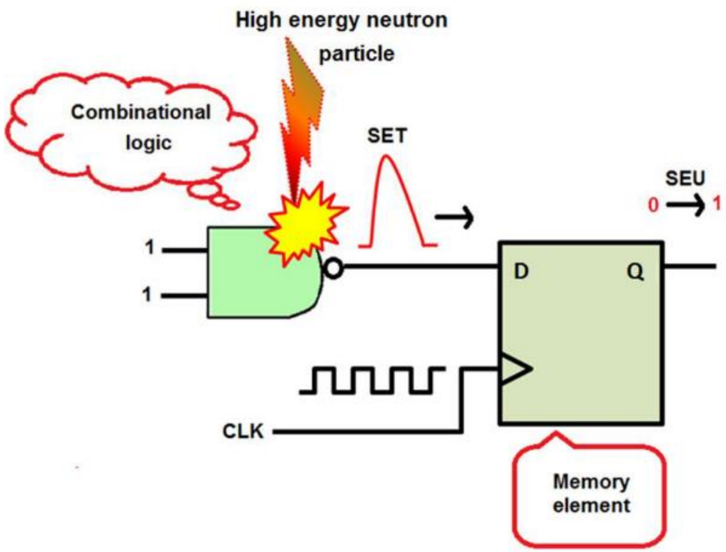
ground measured neutron flux
↓
reconstruction primary proton flux at top atmosphere
↓
propagation through atmosphere accounting for magnetic and atmospheric shielding
↓
conversion particle flux into effective dose
↓
<u>nowcast</u> effective dose at different positions in atmosphere



Single event effects in avionics onboard airplane

- → Single particle can deposit charge in sensitive volume of semiconductors and create transient pulses in logic or support circuitry, or as bitflips in memory cells or registers
- → Soft (non-destructive) and hard (destructive) errors





- → Can also impact Medical Devices
- → pacemakers, defibrillators, or insulin pumps are susceptible to the effects of cosmic radiation

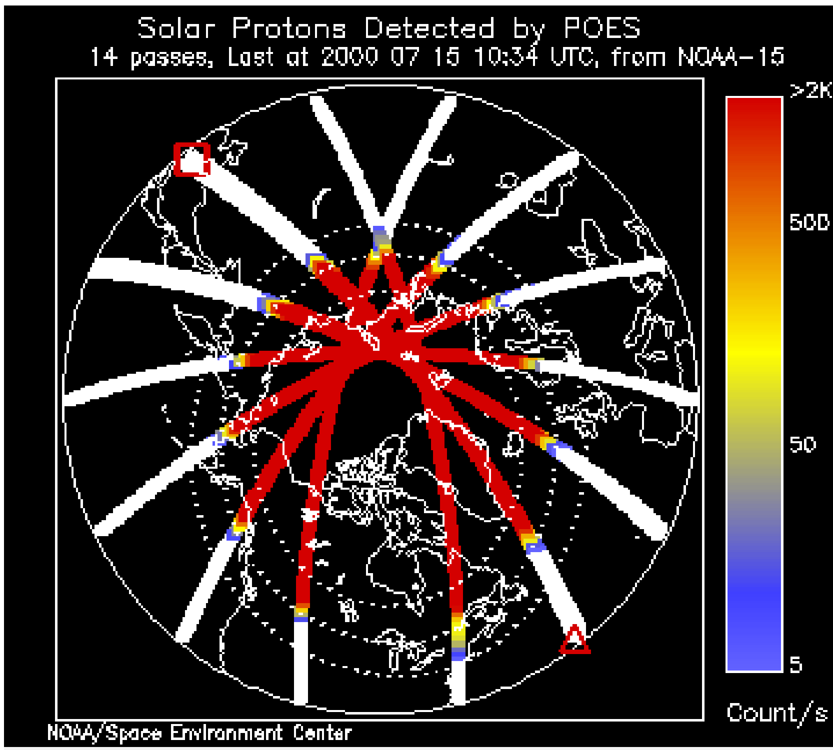
(https://www.bbc.com/future/article/20221011-how-space-weather-causes-computer-errors?ocid=ww.social.link.email)

Polar Cap Absorption (PCA) during SEP events

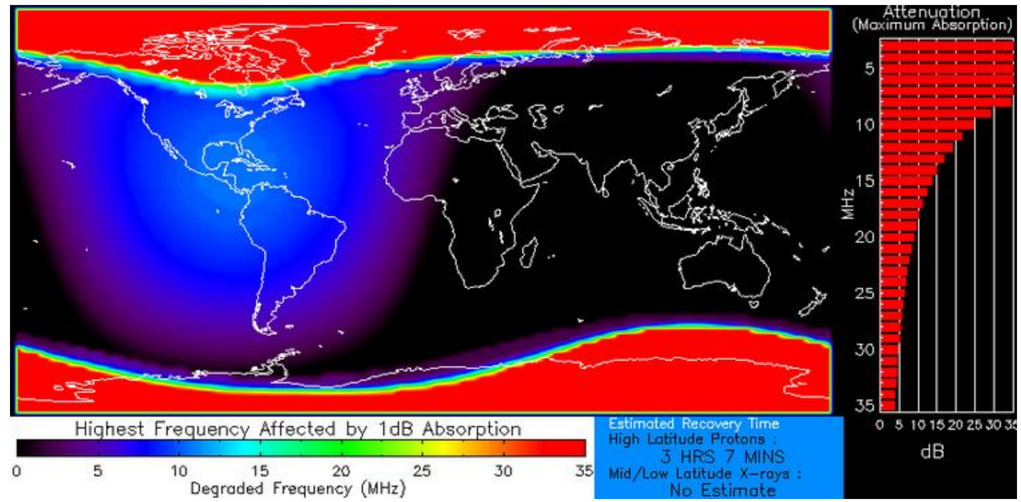
During SEP events, high energy protons (>10 MeV) spiral along the Earth's magnetic field lines towards the polar ionosphere's D-region (50-90 km) (= proton precipitation)

→ Significant increased ionization levels

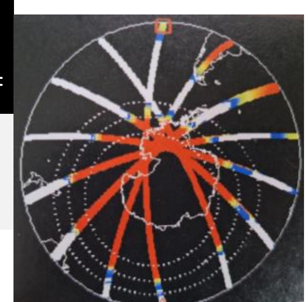
→ Severe absorption of HF radio waves (3 – 30MHz) used for long-range communication



Precipitating proton flux detected on several passes of the POES NOAA-15 satellite over the north polar region during the solar storm of July 15, 2000. (NOAA Space Weather Prediction Center).



Impact of the solar X-ray flux and SEP events on HF radio communication during the solar storm of 9 May 2023. The plot is generated by the D-Region Absorption Product (DRAP). (NOAA Space Weather Prediction Center).

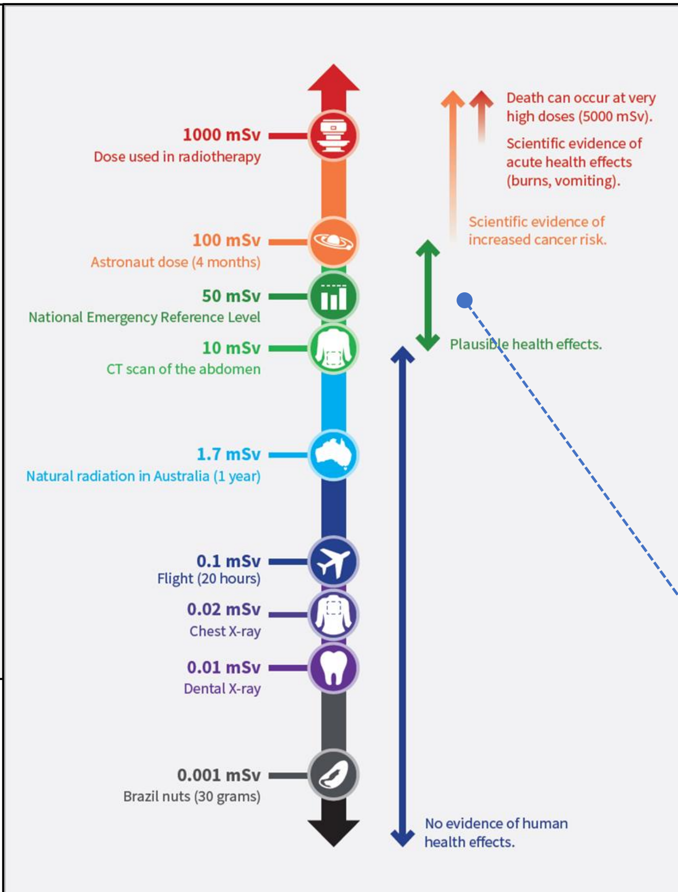


south polar region

In summary: how much radiation from air travel?

In general, **low** but it depends on:

- **Duration of the flight**
  - *Longer → more radiation*
- **Altitude**
  - *Higher → more radiation*
- **Latitude**
  - *Closer to the poles → more radiation*
- **Solar activity**
  - *Higher solar activity → less radiation from GCR but more if strong SEP/GLE (>200-500 MeV)*



https://www.arpansa.gov.au/understanding-radiation/radiation-sources/more-radiation-sources/ionising-radiation-and-health

GLE	Date	Max. E [μSv h^{-1}]	E_{GCR} [μSv h^{-1}]
5	23.02 1956	2977	6.9
8	04.05 1960	57.3	5.0
10	12.11 1960	12.1	5.2
11	15.11 1960	140.5	5.2
13	18.07 1961	13.7	5.4
16	28.01 1967	15.8	6.4
19	18.11 1968	11.4	5.3
22	14.01 1971	25.1	6.2
25	07.08 1972	7.8	6.4
29	24.09 1977	8.8	7.3
30	22.11 1977	15.5	7.7
31	07.05 1978	35.4	6.4
32	23.09 1978	8.1	7.2
38	08.12 1982	22.4	4.7
39	16.02 1984	13.5	6.1
41	16.08 1989	10.8	5.0
42	29.09 1989	92.7	4.8
43	19.10 1989	41.9	4.5
44	22.10 1989	92.5	4.5
45	24.10 1989	61.0	4.5
47	21.05 1990	12.0	4.3
48	24.05 1990	17.0	4.3
51	11.06 1991	6.0	3.5
52	15.06 1991	11.2	3.5
55	06.11 1997	19.9	7.5
59	14.07 2000	48.1	4.9
60	15.04 2001	51.3	5.3
61	18.04 2001	9.0	5.3
65	28.10 2003	12.4	5.4
67	02.11 2003	15.6	4.6
69	20.01 2005	3592	5.9
70	13.12 2006	78.2	7.4
71	17.05 2012	32.9	7.2

(Tuohino et al., 2018 - ~11 km, Rc < 1 GV)

Mitigation Measures

- Delay of flight if not time-critical (~hours)
- Change of flight route:
  - Lower latitude → geomagnetic shielding ↗
  - Lower altitude → atmospheric shielding ↗

  But:
  - Higher fuel consumption
  - Increased traffic density
  - Not necessarily solution for HF COMM degradation
- In-flight monitoring
- Radiation hardening of avionics + onboard redundancy

Aviation community

- Timely forecast/detection SWx events → ICAO advisories

Science community

"Apparently, flying no higher than 1,000 feet saves air travelers from the perceived ravages of cosmic radiation."