University of Ljubljana
Faculty of Mathematics and Physics

Health risks of cosmic rays

Author: Lara Hočuršćak

Adviser: Prof. Matej Lipoglavšek

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Abstract

Cosmic rays are high-energy particles coming from space that hardly ever hit the Earth's surface but interact with nuclei of air molecules, usually several tens of kilometers above ground, and many new particles are formed. However, during air travel we are exposed to cosmic rays and to the energetic products of their interactions with air nuclei. In this seminar I will present data on the received radiation dose due to cosmic rays for two groups that are occupationally exposed to (space) radiation – commercial flights personnel and astronauts. Health risks will be estimated and backed up with study results.

Contents

1 Cosmic rays

Cosmic rays (CRs) are high-energy subatomic particles arriving at Earth from space. Most of them, about 85%, are protons or hydrogen nuclei, 12% are helium nuclei or α- particles, and 1% belongs to heavier nuclei, all the way up to uranium. The rest (2%) are electrons. Cosmic rays include:

- Galactic CRs, that come from outside the Solar System but typically from within the Milky Way galaxy,
- Anomalous CRs, coming from the interstellar space and gaining energy inside Solar system,
- Solar energetic particles, associated with Solar flares and similar events.

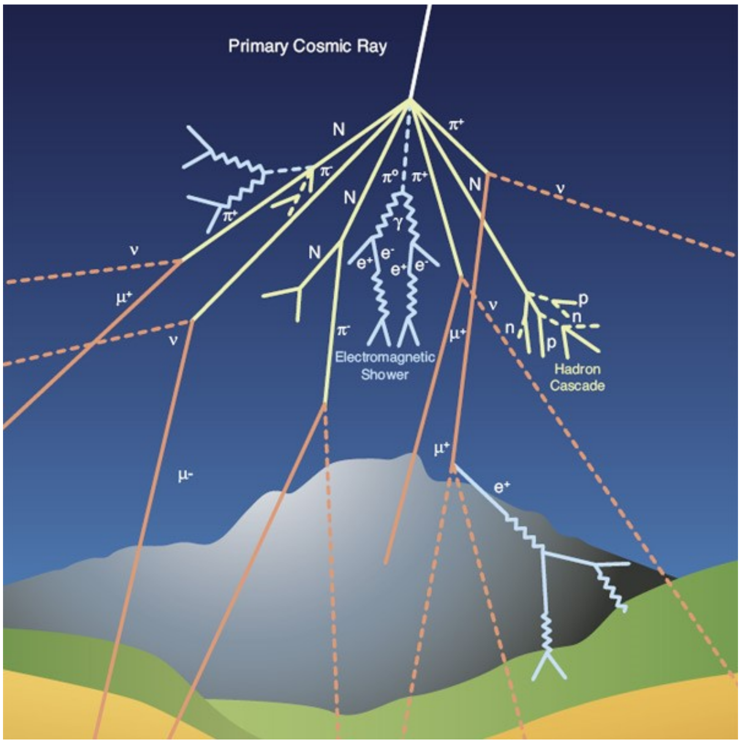

Figure 1: Air showers in the Earth's atmosphere. Primary CRs usually interact at a height of several tens of kilometers. N stands for nucleus, n for neutron, p for proton, e^- for electron, e^+ for positron, $\pi^\pm$ for pions, $\mu^\pm$ for muons, γ for gamma ray and ν for neutrinos [1].

When primary CRs approach Earth, as seen in figure 1, their collision with atomic nuclei in the upper atmosphere creates more particles. These events are called air showers and can be divided into two categories:

- *an electromagnetic shower* occurs when a high-energy photon, electron or positron interacts with an electromagnetic field of the air molecules in the atmosphere, mainly through the processes of pair production and bremsstrahlung, generating a cascade of electromagnetic particles (blue lines in figure 1);
- *a hadronic shower* is initiated only if the primary CR is a hadron. A high-energy hadron interacts with an atmospheric nucleus N by the strong force. Newly formed particles are mostly pions that decay into two gamma-rays (neutral pions) or into a muon and a neutrino – charged pions (orange lines in figure 1)).

Gamma-rays from the neutral pions sometimes create new particles by the pair-production, usually an electron and a positron. Air showers are the main reason CRs hardly ever hit the ground. How many CRs actually arrive at surface depends on the energy of CRs and the altitude above sea level. Particles mostly arrive at the ground within a few hundred meters from the axis of motion of the original particle, so called the shower axis. However, some particles can be found even kilometres away from this axis. Muons are the most numerous charged particles at the ground. Most of the muons are produced in the atmosphere, typically 15 km above the sea level [2, 3, 4, 5].

1.1 Energy spectrum of CRs

The spectrum of CRs is their best known characteristic, extending over 12 orders of magnitude in energy W. In figure 2, CR flux measurements at different energies per particle are shown. Flux reaching the Earth is proportional to $W^2 I(W)$, where W is the kinetic energy and $I(W)$ is the number of particles arriving per unit interval of time, area, solid angle and kinetic energy. The units of differential intensity $I(W)$ are therefore $\left[\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}\text{GeV}\right]$. In the energy range from several GeV to somewhat beyond 100 TeV (10^5 GeV), $I(W)$ is given approximately by the power-law:

$$I(W) \propto W^{-2.7}. \tag{1}$$

When kinetic energy exceeds 10^5 GeV, the flux is too low to clearly identify the particles directly, which is typically measured with detectors, carried by balloons or satellites. What can be measured is the total flux of all particle types, which is recorded by air shower experiments. After the downward bend near $10^{6.5}$ GeV, called the *knee*, the flux falls more steeply to the energies near 10^{10} GeV, so called *ankle*. Measurements take values up to several 10^{11} GeV (10^{20} eV). Beyond the ankle, the CR fluxes measured in different experiments are not entirely consistent [6].

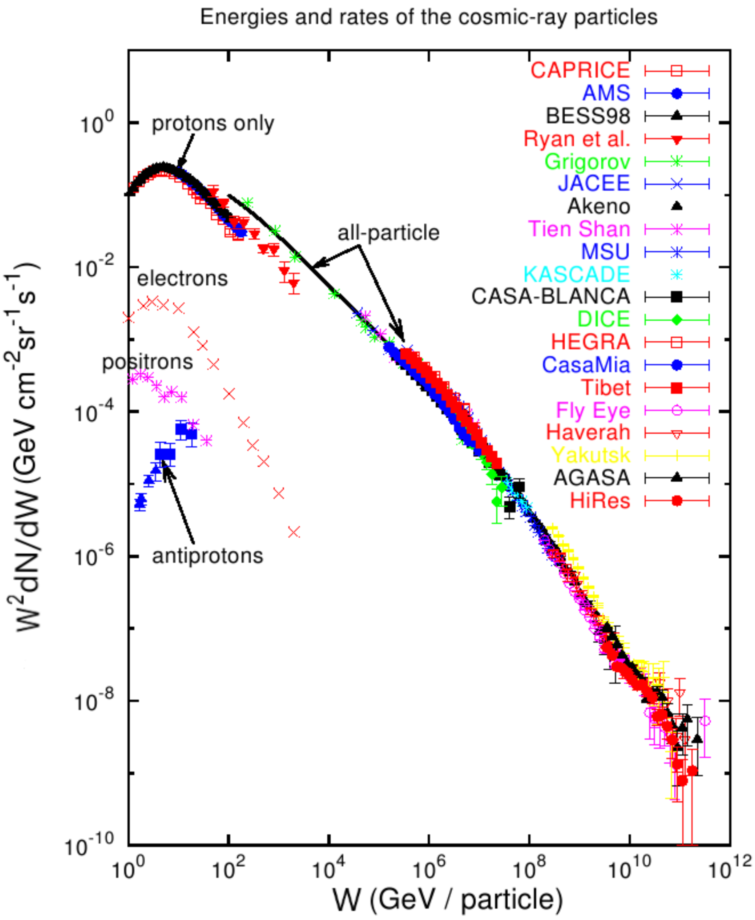

Figure 2: Measurements from a series of experiments of the CR flux over a wide kinetic energy range. Experiments use different techniques at different altitudes – from air fluorescence (HiRes) and LIDAR (Yakutsk), to Cherenkov detectors (HEGRA, CAPRICE) and others. Experiments that detected CRs with the highest energies are all located on the ground (HiRes, AGASA, Yakutsk, Haverah, Fly Eye) [6].

2 Dosimetric quantities

Firstly we will define some of the dosimetric quantities we will be using afterwards. Absorbed dose, D, is defined as the quotient of mean energy, $\mathrm{d}\bar{\epsilon}$, imparted by ionising radiation in a volume element, and the mass, $\mathrm{d}m$, of the matter in that volume: $D = \mathrm{d}\bar{\epsilon}/\mathrm{d}m$. The SI unit is Jkg^{-1} or gray (Gy). Absorbed dose is defined at any point in matter and, in principle, is a measurable quantity [7].

Radiation-weighted dose in an organ or tissue (also known as equivalent dose), H_T, is defined by: $H_T = \sum_R w_R D_{T,R}$, where $D_{T,R}$ is the mean absorbed dose in a tissue T due to radiation of type R and w_R the corresponding radiation weighting factor, mainly based upon experimental values. The sum is performed over all types of radiations involved. The unit of radiation weighted dose is Jkg^{-1} or sievert (Sv) [7]. Heavy particle radiation deposits energy at a faster spatial rate – it has a greater ability to cause irreversible damage. Alpha particle radiation has 20 times higher rate of energy transfer than the gamma and X-rays. For alpha particle radiation, the weighting factor is 20, compared to gamma and X-ray radiation with weighting factor 1 [8].

Linear energy transfer (LET) is the average energy locally transfered to the medium by a charged particle per unit track. High LET radiation or densely ionizing radiation (such as alpha or neutron radiation) deposits a large amount of energy in a small distance, which leads to a larger biological effect – more potential damage to the DNA. Oppositely, low LET radiation or sparsely ionizing radiation (X, gamma or beta radiation) has a smaller biological effect [9].

Effective dose, E, is defined by: $E_{T,R} = \sum_T w_T \sum_R w_R D_{T,R}$, where w_T is the tissue weighting factor with $\sum w_T = 1$. The sum is performed over all organs and tissues of the human body considered in the definition of E. The unit of effective dose is also sievert. The bigger the weighting factor, the more sensitive the body part is to radiation. If the whole body is exposed, effective dose is same as equivalent dose, since the sum of weighting factors equals 1. Weighting factors are used when only a part of the body is exposed, which is usually the case in medical imaging. Effective dose is a quantity, used for evaluating the stochastic health risk and it is not a measurable quantity [7, 8].

Since we are not able to measure the effective dose directly, there has been a new, measurable quantity introduced – ambient dose equivalent, $H^*(10)$. For area monitoring, the operational quantity for strongly penetrating radiation (those with high LET) is $H^*(10)$ and it is defined by: at a point of interest in the real radiation field $H^*(10)$ is the dose equivalent that would be produced by the corresponding aligned and expanded radiation field, in the ICRU sphere at a depth of 10 mm, on the radius opposing the direction of the aligned field. So-called ICRU sphere is a phantom approximating the human body and it is made of 30-cm-diameter tissue-equivalent plastics with a density of 1 g/cm^3 and a mass composition of 76.2 % oxygen, 11.1 % carbon, 10.1 % hydrogen and 2.6 % nitrogen [7, 10].

The (worldwide) average dose received by an adult person is 3 mSv/year, of which 2.4 mSv/year come from natural sources of exposure – terrestrial radiation from Earth (2 mSv/year) and cosmic radiation (0.4 mSv/year). Terrestrial radiation includes naturally radioactive rock, soil, water, air, food etc., where radon in air contributes more than half of the dose. The average dose from medical diagnosis contributes the rest, i.e. 0.6 mSv/year to the dose from natural sources [11].

3 Cosmic radiation exposure

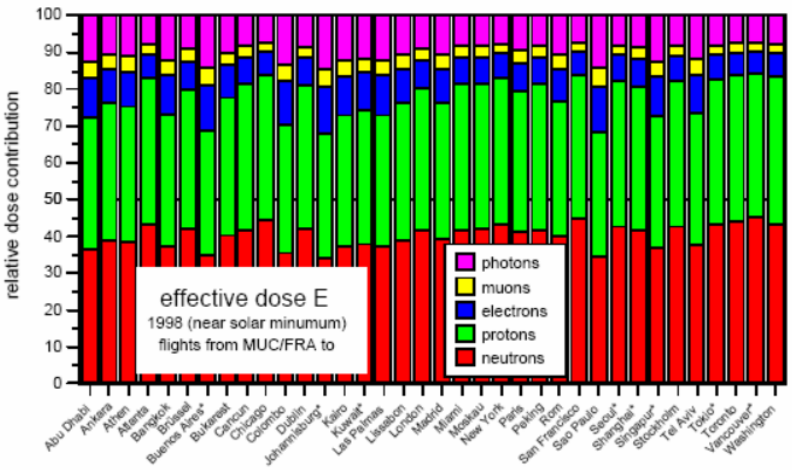

Figure 3: Relative contribution to effective dose during commercial flights for various destinations (departing from Munich or Frankfurt, measurements made at altitude of 11 km) near minimum solar activity [13].

The CRs we are exposed to during air travel are mostly galactic. They are nearly isotropic at most energies due to deflection of charged particles in the intergalactic magnetic field. Solar CRs have lower energy than galactic CRs, so their effects are mostly limited to the upper atmosphere (above 30 km) [12]. The solar activity affects the received radiation dose. Secondary CRs that are formed in the atmosphere in air showers (neutrons, pions, muons, electrons, photons and secondary protons), together with the primary CRs cause greater radiation exposure during air travel than at the Earth's surface. Neutrons contribute around 40 % percent to the total dose at flying altitudes (fig. 3). Due to the high radiation-weighting factor for protons ($w_R = 5$), their contribution to the effective dose is the next most important [14].

3.1 Radiation exposure during commercial flights

Galactic CRs contribute the most to the aircrew exposure to radiation – around 95 %. Radiation dose level represents a complex function of the following:

- it is modulated by Solar activity and the position in its 11-year cycle (fig. 4). Solar activity peaks approximately every 11 years when sunspot number reaches a maximum. At these times fewer CRs reach Earth, because the Sun emits plasma and magnetic fields which expel some of the CRs from the solar system.
- it increases with flight altitude up to 20 km. Measurements are made from 5 to 15 km of altitude (fig. 5).
- it is a function of latitude – radiation shielding by the geomagnetic field is the greatest at the equator and decreases as one goes south or north from the equator. In figure 5, calculated ambient dose equivalent at zero-meridian and geographic latitude of 0° (red lines) and 90° (blue lines) are shown. The effect of the Earth's magnetic field is described with a parameter *cutoff rigidity*, which represents roughly the lowest rigidity limit above which CRs can cross the Earth's magnetosphere and reach a specific position. Particles entering the Earth's magnetic field at the equator can penetrate through magnetic field only if their energy exceeds 15 GeV, whereas for particles entering at the pole region there are no restrictions. The reason are the magnetic field lines around Earth. In figure 6 cutoff rigidity values are shown [13].

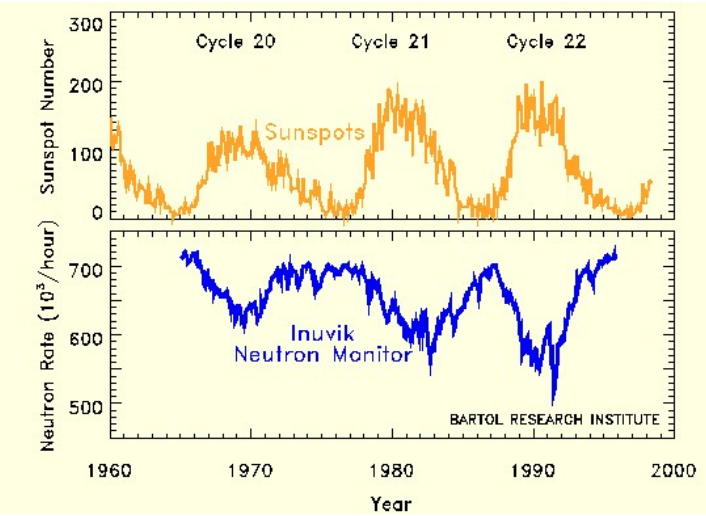

Figure 4: Anti-correlation of sunspot number (linked to solar activity) and neutron counts. The CR data was recorded by the Inuvik neutron monitor which detects CRs by detecting neutrons. Inuvik is geographically well located – close to the pole, so Earth's magnetic field allows neutrons to be created closer to the ground [15].

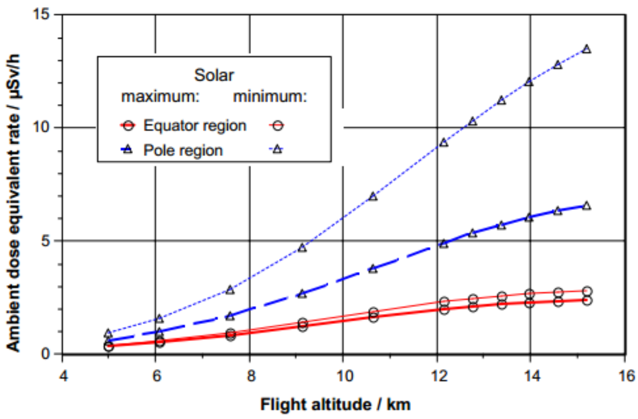

Figure 5: Calculated ambient dose equivalent for conditions close to solar maximum (thick lines) and minimum activity (thin lines) [13]

3.1.1 Calculated exposures of Adria Airways personnel

A computer program CARI 6 was used to calculate the exposures of Adria Airways (AA) personnel to galactic cosmic radiation [13]. The effective doses were evaluated for the flights during average, maximum and minimum solar activity. Three homogeneous groups were identified: pilots of Canadair CRJ, cabin crew and pilots of Airbus A320. Additionally there were some direct radiation measurements during AA flights performed which will be presented later on. The calculations showed that the cosmic radiation exposure per year was about 2.4 times higher on an Airbus A320 plane compared to the CRJ plane. The main reasons are that an A320 generally flies at higher altitudes, spends 30% more time in the air compared to the CRJ planes, which also means that CRJs spend more time at lower altitudes (when taking off and landing). At a minimum solar activity, radiation dose per year is about 20% higher than at a solar maximum. Both types of Adria Airways' planes (A320 and CRJ) are operated by one of the three types of pilots: instructors, captains or co-pilots. There are 9 instructors, 13 captains and 15 co-pilots operating A320 planes and 12 instructors, 18 captains and 36 co-pilots operating CRJs. Based on the data from 2004, effective dose per year has been estimated for pilots on both of the planes and is shown in figures 7 and 8. Aside from the pilots, there is also cabin crew present on board and is exposed to cosmic radiation as well (fig. 9). To conclude from figures 7 to 9, we estimate typical effective dose to be: for A320 pilots approximately 3 mSv per year, for cabin crew approximately 2 mSv per year and for CRJ pilots approximately 1 mSv per year. AA flight personnel is not expected to receive an effective dose exceeding 6 mSv per year for their flying frequency and destinations they are currently flying to [13].

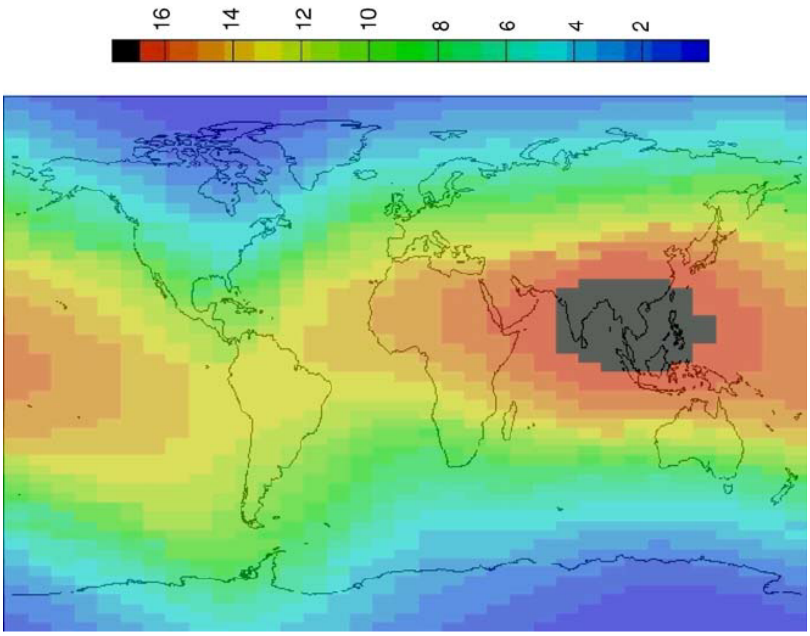

Figure 6: The vertical effective cutoff rigidity as a function of latitude and longitude for observer at 20 km altitude for year 1982 [16].

Category	BT (h/year)	<E> (mSv/year)	E_{min} (mSv/year)	E_{max} (mSv/year)
Instructor	930	2.83	2.50	3.08
Captain	940	2.86	2.53	3.11
Co-pilot	1000	3.04	2.69	3.31

Figure 7: Effective dose for AA pilots of A320 planes in 2004. BT (block time) is the total flight time and E is effective dose for each group of pilots (their average, minimum and maximum values) [13].

Category	BT (h/year)	<E> (mSv/year)	E_{min} (mSv/year)	E_{max} (mSv/year)
Instructor	590	0.97	0.86	1.07
Captain	700	1.15	1.02	1.27
Co-pilot	680	1.12	0.99	1.23

Figure 8: Effective dose for AA pilots of CRJ planes in 2004. BT (block time) is the total flight time. Average radiation exposure is more than two times lower in CRJ compared to A320 [13].

Category	Number	BT (h/year)	<E> (mSv/year)	E_{min} (mSv/year)	E_{max} (mSv/year)
Instructor	13	915	2.0	1.8	2.2
Cabin crew	56	944	2.1	1.8	2.3

Figure 9: Effective dose for cabin crew of A320 and CRJ planes in 2004. Comparison with instructors (data for both types of planes is combined) is made [13].

3.1.2 Direct measurements on Adria Airways planes

Direct measurements of radiation were made on all of the AA planes. Thermoluminescent dosimeters (TLD) for personal dose monitoring were used, one with and another without a charged particle filter (fig. 10). These dosimeters are sensitive to ionizing cosmic radiation but they cannot detect neutrons, which is not negligible. Neutrons contribute 35 to 45 % to overall effective dose when air travelling. TLDs were used to estimate dose for flights at various altitudes. Average dose rate measured with TLD by the type of the plane is: $\mathrm{d}D/\mathrm{d}t = (0.96 \pm 0.06)$ µSv/h for A320 and $\mathrm{d}D/\mathrm{d}t = (0.72 \pm 0.06)$ µSv/h for CRJ. Radiation levels were higher on A320 planes for 33% compared to CRJ, since they normally fly at higher altitudes. Measured dose is probably underrated, so we conclude that TLDs are not to be used for quantitative evaluation [13].

Additionally, on one of the AA flights (Ljubljana – Copenhagen – Ljubljana) ionization chamber Reuter-Stokes RSS-112 was used for monitoring ionizing cosmic radiation, and Berthold LB6411 neutron dose-rate meter for neutron detection. The goal was to compare measured dose as a function of latitude and altitude to calculations. Dose rate is mainly altitude-dependent (fig. 11) and it is increasing with latitude – flight towards Copenhagen is almost due north (fig. 12). In figure 13, dose rate as a function of altitude is presented. A passenger flying from Ljubljana to Copenhagen and back would have received 4 µGy absorbed dose and 2.9 µSv effective dose (comparable to natural background radiation for about half a day) [13]. For comparison, an intraoral X-ray results in 5 µSv received effective dose, a flight from Frankfurt to New York and back results in an average effective dose about 100 µSv [17] and 2 mSv for a CT scan of head (among the lowest doses received by CT) [18].

Office	D_{tot} (µSv)			$T_{airplane}$ (hours)	$D_{airplane}$ (µSv)	$dD/dt_{airplane}$ (µSv/h)
	TLDF	TLD	(TLDF+TLD)/2			
Ref.	102	103	102	1416	0	0.072
AA	180	208	194	111.73	100	0.895
AB	289	292	290	198.4	202	1.02
AC	250	238	244	158.0	153	0.968
AD	176	161	168	89.25	72	0.806
AE	198	192	195	162.13	105	0.648
AF	216	213	214	169.95	124	0.730
AG	217	220	218	181.0	129	0.713
AH	192	203	197	163.33	107	0.655
AI	221	229	225	173.98	136	0.782
AJ	223	210	216	177.57	127	0.715

Figure 10: TLD dosimetry on AA planes. D_{tot} is the overall dose that TLD with filter (TLDF) or without one (TLD) received. $D_{airplane}$ is the dose received during flights, $T_{airplane}$ is the total time spent flying and $\mathrm{d}D/\mathrm{d}t_{airplane}$ is the average dose rate [13].

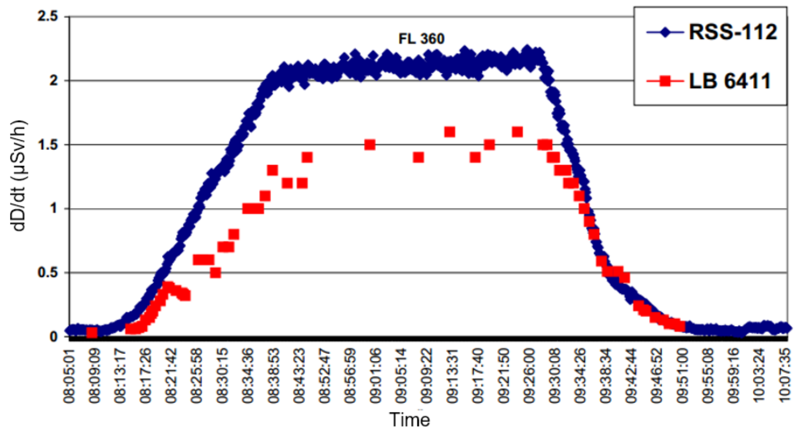

Figure 11: Dose rate of ionizing cosmic radiation. Gamma-rays (RSS-112) and neutrons (LB 6411) were measured on the AA flight from Ljubljana to Copenhagen. Flight level FL360 corresponds to an altitude of 11 km [13].

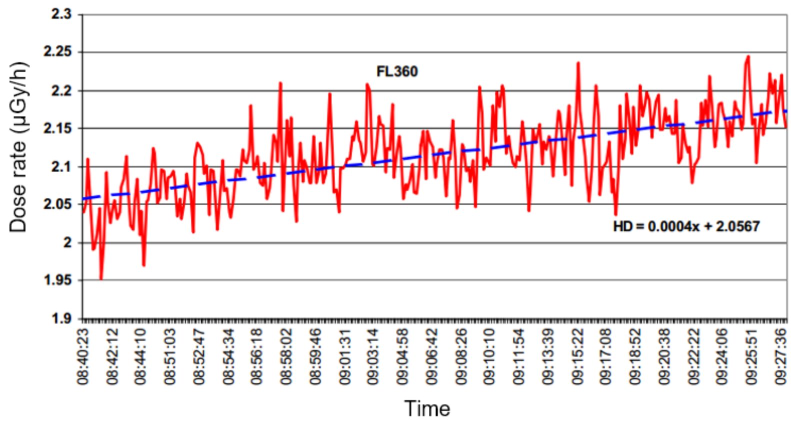

Figure 12: Increasing dose rate on the AA flight from Ljubljana to Copenhagen (to the north) at the same flight level – altitude 11 km [13].

3.1.3 Health risks

Effective dose that Adria Airways personnel receives is from 1 mSv/year to 3 mSv/year in addition to around 3 mSv/year for a person not occupationally exposed to radiation. Significantly greater risks for cancer and other health issues are not expected. As mentioned before, AA flight personnel should not receive an effective dose more than 6 mSv/year. Increased lifetime risk of fatal cancer because of occupational exposure to ionizing radiation is 1 in 4200 for 6 mSv/year effective dose (compared to 1 in 8300 for 3 mSv/year). Increased risk of severe genetic defect is notable for effective dose over 10 mSv/year and therefore it is not expected for AA aircrew. A pregnant aircrew member could work 2 months without the dose to the conceptus exceeding the recommended pregnancy limit of 1 mSv [19].

3.2 Astronauts' exposure to radiation

Similar to aircrew, astronauts are also exposed to (mostly) galactic cosmic radiation. There are three main factors that determine the amount of radiation that astronauts receive: altitude above the Earth (Earth's magnetic field is weaker and spacecraft pass through the zones of charged particles, trapped by Earth's magnetic field), solar cycle and individual's susceptibility to radiation. Because the levels of protection vary, the radiation environments vary between planets and moons, even at different places on the surface of individual planets. For example, the International Space Station (ISS) has well-shielded areas and the astronauts are largely protected by the Earth's magnetic field because the ISS is in a low Earth's orbit. In contrast, during a deep space journey to the Moon or Mars, astronauts and their vehicles will venture far outside of the Earth's protective magnetic shield. The typical average natural dose for a person is about 3 mSv/year, which is a small dose. International Standards allow exposure to as much as 50 mSv/year for those who work with and around radioactive material. For space-flight, the limit is higher. The NASA limit for radiation exposure in low Earth's orbit is 0.50 Sv/year, or 500 mSv/year. Note that the values are lower for younger astronauts.

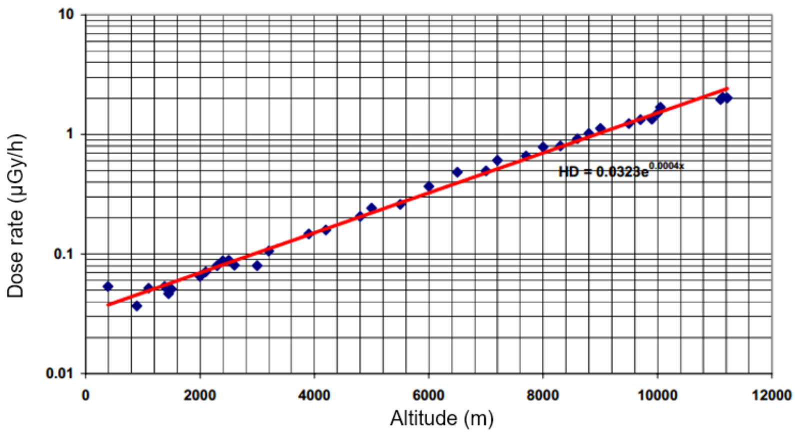

Figure 13: Dose rate increasing exponentially with altitude. Measured by RSS-112 on a flight from Ljubljana to Copenhagen [13].

Age (years)	25	35	45	55
Male	1.50 Sv	2.50 Sv	3.25 Sv	4.00 Sv
Female	1.00 Sv	1.75 Sv	2.50 Sv	3.00 Sv

Figure 14: Career exposure limits for NASA astronauts by age and gender [20].

Mission type	**Radiation dose**
Space Shuttle Mission 41-C (8-day mission orbiting the Earth at 460 km altitude)	5.59 mSv
Apollo 14 (9-day mission to the Moon)	11.4 mSv
Skylab 4 (87-day mission orbiting the Earth at 473 km altitude)	178 mSv
ISS Mission (6 months orbiting the Earth at 353 km altitude)	160 mSv
Estimated Mars mission (3 years)	1200 mSv

Figure 15: Average radiation dose received by the mission type [20].

The career length equivalent dose limit is based upon a maximum 3 % lifetime excess risk of cancer mortality – the total equivalent dose yielding this risk depends on gender and age at the start of radiation exposure. Figure 15 compares various missions and their durations with the observed radiation dose. Crews aboard the space station receive an average of 80 mSv for a six-month stay at solar maximum and an average of 160 mSv for a six-month stay at solar minimum. The difference in received dose at solar minimum and maximum is bigger for astronauts than the aircrew of commercial flights [20].

3.2.1 Health risks

Possible health risks include cancer, damage to the central nervous system, cataracts, risk of acute radiation sickness, and hereditary effects. Risk of cancer death for astronauts by missions in presented in figure 16.

At this time, reliable projections for central nervous system (CNS) risks from space radiation exposure cannot be made due to limited data on the effects of high radiation on the nervous system. Acute (during missions) and late CNS risks from space radiation are of concern for exploration missions beyond low Earth's orbit (ISS), including missions to the Moon, asteroids, or Mars. The association between ionizing radiation exposure and the long-term development of degenerative tissue effects such as heart disease, cataracts, immunological changes, and premature aging is well-established for moderate to high doses of radiation. The majority of this evidence is derived from studies on the atomic bomb survivors in Japan, radiotherapy patients, and occupationally exposed workers and is supported by studies of cataracts in astronauts. These risks remain debatable for ISS or short-term Lunar missions but are more likely in long-term Lunar or Mars missions.

The development of ocular cataracts, which is a degenerative opacification of the crystalline eye lens, is a well-recognized late effect of exposure to ionizing radiation. In figure 17, cumulative lens dose received by astronauts is seen. The comparison shows individual contributions from space radiation exposures measured by radiation badges with corrections, from diagnostic X-rays and other medical procedures, and from occupational air training. The biggest contribution to the total dose is space travel. Hazard ratios show a significant increase in cataract risk for astronauts in the high space lens dose group (lens doses above 8 mSv, average 45 mSv) compared to astronauts in the low space lens dose group (lens doses below 8 mSv, average 4.7 mSv). Prevalence of cataracts at the age of 70 for commercial pilots is 3 times larger than in healthy US males; for low-dose astronauts it is 7 times larger and becomes 9 times larger for high-dose astronauts than

US male average as shown in figure 18.

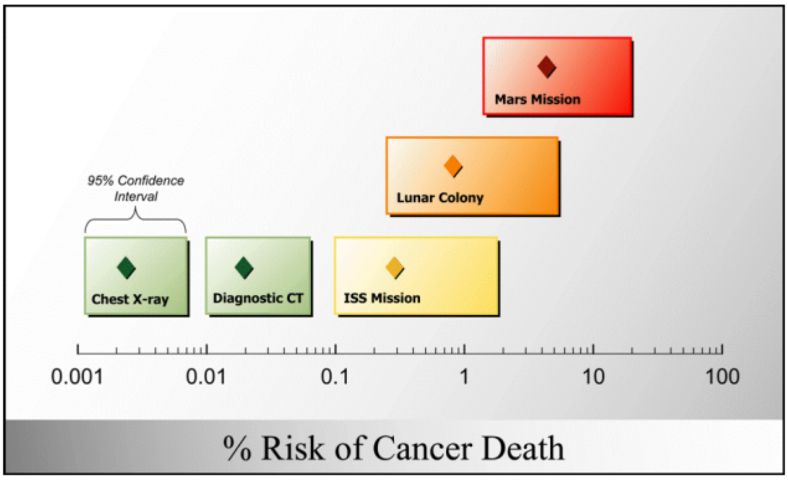

Figure 16: The figure shows current estimates of cancer risks and 95 % confidence bands for adults at the age of 40, the typical age of astronauts on space missions, for several terrestrial exposures and missions. The uncertainties are larger for astronauts in space compared to typical exposures on Earth [21].

The biological effects of space radiation, including acute radiation risks (ARS), are a significant concern for manned space-flight. The primary data that are currently available are derived from analyses of medical patients and persons accidentally exposed to high doses of radiation. Radiation protection must be provided in the form of shielding and operational dosimetry and monitoring, as well as biological countermeasures when travelling outside of the protective magnetosphere of the Earth. As future NASA missions once again extend beyond lower Earth's orbit and for longer durations, there is reasonable concern that a compromised immune system due to high skin doses from a solar particle event may lead to increased risks [21].

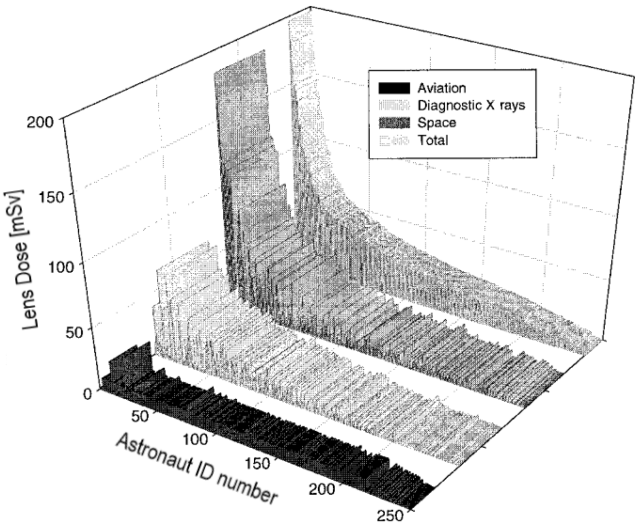

Figure 17: The cumulative lens dose for each astronaut from space, aviation and medical procedures, participating in the LSAH study [22].

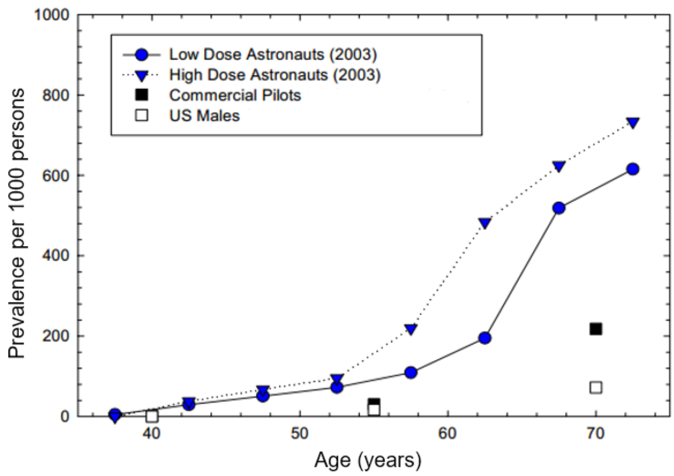

Figure 18: Prevalence of cataracts as a function of age in astronauts, pilots and healthy US males [23].

4 Conclusion

As a consequence of being an aircrew member for commercial flights greater health risks apply. Effective dose for Adria Airways aircrew is on average from 1 to 3 mSv/year but lower than 6 mSv/year. Increased life-time risk of fatal cancer is twice as big for 6 mSv/year dose compared to 3 mSv/year (dose for an average person living on Earth's surface). Another study has shown that pilots were three times as likely to have nuclear cataracts compared to the non-pilots. When estimating effective dose for astronauts it is important to know whether they are on a mission in low Earth's orbit (ISS) or high Earth's orbit (mission to the Moon or Mars). ISS' astronauts are protected by the Earth's magnetic field. When travelling to the Moon or Mars, there is no more magnetic protective shield of the Earth. For astronauts, NASA limit for radiation is therefore 500 mSv/year on average for low Earth's orbit. Per career, an astronaut may receive up to 3 % lifetime excess risk of cancer mortality. Crews aboard the ISS receive an average of 80 to 160 mSv/6-month-period (depending on the solar maximum/minimum). Possible health risks include cancer, damage to central nervous system, cataracts, risk of acute radiation sickness and hereditary effects. In low Earth's orbit these health risks are not as significant as they would be when travelling for longer time and outside the Earth's magnetic field (for example mission to Mars). Prevalence of cataracts at the age of 70 for low-dose astronauts is 7 times larger and it is 9 times larger for high-dose astronauts than an average healthy US male. For future missions outside the Earth's magnetic field there has to be additional protection provided and health risk studies made.

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