



Occupational Exposure to Cosmic Ionizing Radiation of Aircrew and Astronauts

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Abstract: Aircrew are exposed to ionizing radiation at cruising altitudes, where exposure levels depend on altitude, latitude, and flight duration. Astronauts experience substantially higher exposure due to cosmic radiation of greater energy and linear energy transfer. This review summarizes current knowledge on occupational ionizing radiation exposure among flight and space personnel. A literature search of peer-reviewed and institutional sources was conducted to identify data on exposure levels and regulatory frameworks. Relevant publications and reports from international agencies were examined to compare aircrew and astronaut exposure contexts. Findings indicate that commercial aircrew experience exposure levels well below the established occupational limits, although variations occur depending on flight profiles and routes. For astronauts, space agencies define career dose limits that account for mission type and environment, ensuring exposure management tailored to specific mission conditions. Average effective doses and equivalent doses are reported and discussed for respectively aircrew and astronauts. These limits are established to maintain radiation exposure below levels considered acceptable for professional safety, thereby ensuring regulatory protection under normal operational conditions.

Keywords: cosmic ionizing radiation; occupational exposure; aircrew; astronauts

1. Introduction

Aircrew and astronauts are the main occupational groups exposed to Cosmic Ionizing Radiation (CIR), a unique environmental hazard associated with aviation and spaceflight. In contrast, occasional and frequent flyers are generally expected to remain within exposure limits established for the general public. Within the European Union, occupational exposure to ionizing radiation is defined by the Council Directive 2013/59/EURATOM [1], which incorporate recommendations from the International Commission on Radiological Protection (ICRP) [2–5]. Under this framework, aircrew meet the criteria for classification as occupationally exposed workers, whereas astronauts are considered a special category for whom exposure exceeding standard occupational limits may occur therefore require special authorization and mission-dependent risk assessment. In the United States, the Federal Aviation Administration (FAA) recommends adherence to the ICRP guidance, complemented by the National Council of Radiation Protection and Measurements (NCRP) recommendations [6].

CIR is composed of high-energy particles, primarily atomic nuclei, of extraterrestrial origin and particles generated by interaction with the atmosphere and other matter. Primary particles originate from outside the solar system (Galactic Cosmic Radiation, GCR) or from the sun (Solar Cosmic Radiation, SCR). GCR, mainly protons



and heavier nuclei, reach the solar system from all directions and interact with the electromagnetic field generated by the sun. SCR is continuously emitted and is occasionally accelerated by sudden and unpredictable local outburst of solar matter (Solar Particle Event, SPE), potentially causing exposure to very high CIR doses. The charged particles emitted from the sun can deflect and modulate the GCR intensity but still reach the Earth's orbit. For these reasons, the sun is both a source and a protection from CIR. Solar activity and GCR fluence rate are in fact inversely correlated [5]. GCR particle intensity varies from $1.5 \text{ particles} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ near sunspot maximum, to about $4 \text{ particles} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ near sunspot minimum [7]. Paths of CIR particles are bent as they cross the magnetic field of the Earth, which acts as a partial shield against charged particles, deflected at the geomagnetic equator and trapped at the poles [5]. Trapped particles then influence the overall atmosphere ionization, creating secondary particles that impact the crew in both spacecraft and aircraft.

This narrative review aims to summarize the current knowledge on CIR exposure in aircrew and astronauts, in particular emphasis on exposure characteristics of the regulatory framework governing occupational risks.

2. Materials and Methods

This narrative review is based on descriptive analysis of reports and publications from international agencies, integrated with a structured literature search conducted in PubMed/MEDLINE using the following query: (“ionizing radiation” OR “cosmic radiation” OR “galactic radiation”) and (“astronaut” OR “ISS” OR “aircrew” OR “flight personnel” OR “flight staff”) and (“occupational exposure” OR “dose assessment” OR “risk assessment” OR “dosimeter”). The search was last consulted on 10 January 2025, filtered for publications from 2010 to 2025 and in the English language. In total, approximately 187 records were screened, of which 76 reports were retained. Inclusion criteria were studies reporting occupational dose estimates for aircrew or astronauts, as well as regulatory documents reporting dose limits. Exclusion criteria were non-English studies. Additional relevant studies cited in the included articles were retrieved and assessed when considered pertinent.

Grey literature was systemically reviewed from key institutional sources, including the International Atomic Energy Agency (IAEA), International Civil Aviation Organization (ICAO), the Italian national entity for civil aviation (Ente Nazionale per l'Aviazione Civile, ENAC), International Commission on Radiological Protection (ICRP), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and National Aeronautics and Space Administration (NASA). Searches were conducted using combinations of specific keywords: aircrew/aviation/astronaut, cosmic radiation/ionizing radiation, effective dose/absorbed dose.

Data extracted from the selected sources were categorized into three analytical domains: environmental (e.g., physical characteristics of the radiation, dose rate, altitude, geomagnetic latitude and Solar Particle Events), operational (e.g., determinants related to the work performed, such as flight route, annual flight time, professional status for aircrew, and mission type for astronauts) and occupational (e.g., actual doses received by workers). This framework enables a structured comparison of exposure scenarios and supports the integration of occupational health considerations discussed in subsequent sections.

Occupational exposure in aircrew is primarily assessed using annual average effective dose. These data were primarily derived mainly from UNSCEAR Occupational Exposure survey, which evaluated CIR exposure in civil aviation across 22 countries. The analysis is focused on the periods 2000–2004, 2005–2009 and 2010–2014 for Countries with updated data, while earlier periods (1990–1994 and 1995–1999) were included for countries lacking more recent contributions following the 2008 UNSCEAR report. In addition to average annual effective dose, data on workforce size and ICAO global estimate were. Countries with insufficient or missing data (e.g., Japan) were excluded [8].

For astronauts, occupational exposure is evaluated using equivalent dose rather than effective dose. Terrestrial radioprotection frameworks are designed to limit exposure to minimize stochastic effects and prevent deterministic effects, as further discussed in Section 3.3 (“Occupational health considerations”). In practice, dose limits are defined in terms of effective and equivalent doses referred to the whole-body or organ-specific exposure. Effective dose is derived by averaging organ equivalent doses using weighting factors based on epidemiological data, primarily obtained from low-LET radiation (e.g., X-rays and gamma-rays). While these weighting factors are appropriate for aircrew, they may underestimate the effects in astronauts, who are exposed to significant levels of high-LET radiation (e.g., protons, heavier nuclei, neutrons), for which human epidemiological data remains limited. For this reason, equivalent dose is used in this review as more appropriate metric for assessing individual risk exposure in spaceflight conditions [9].

The following sections integrate environmental, operational and occupational dimensions to structure the analysis of CIR exposure and its occupational health implications in aircrew and astronauts.

3. Results and Discussion

3.1. Commercial Aircrew's Exposure

Commercial aircrew includes pilots, who operate the aircraft, and cabin crew, who are responsible for in-flight services. Both are occupationally exposed to physical agents that may affect health, including air pressure variations, noise, vibrations, CIR and temperature fluctuations [10]. The global number of civil aviation workers has increased overtime, reaching approximately 900,000 workers during the period 2015–2019 [8].

With respect to CIR, the radiation field on aircraft is modulated by altitude, geomagnetic latitude, and solar cycle. The Earth's atmosphere absorbs and screens charged particles, generating secondary particles that propagate toward the ground. At typical aviation altitude (8–12 km above sea level), and particularly at the equatorial latitudes, electrons/positrons and neutrons represent contributors to dose, followed by protons. At higher latitudes, neutron contribution becomes predominant, while at higher altitudes, heavier nuclei increasingly contributes to the radiation field [5]. Operational data on flight route and altitude suggest that at normal aviation altitude, the dose rate can reach 7 $\mu\text{Sv/h}$, more than 150 times the CIR exposure at sea level. At higher altitudes, as those reached by the Air France Concorde (i.e., maximum 18 km above sea level), dose rates significantly increase, reaching 9.5 $\mu\text{Sv/h}$ at solar minimum on a Paris-New York flight [5]. Exposure levels are higher in polar regions and lower near the geomagnetic equator due to the reduced shielding effects of the geomagnetic field at high latitudes. Route-based dose comparisons show an increase from 25 to 30 μSv on the trans-equatorial flight (i.e., Frankfurt-Johannesburg) and from 50 to 78 μSv on the polar routes (i.e., Frankfurt–New York) [11]. SPEs can further increase CIR exposure levels and are indirectly detected as ground-level enhancements using neutron monitors. In-flight measurements have reported peak dose of up to 1.7 mSv/h during a single flight [12] with increase of up to about 80% of the total dose for the polar flights [13].

Due to the complexity of the radiation field at aviation altitudes, dose assessment is not typically based on individual dosimetry. Instead, exposure is routinely estimated using validated computational models and algorithms calibrated against experimental data [14]. The radiation dose associated with a specific flight depends on altitude profile, latitude, and the duration, while the annual individual dose is determined by the combination of flight routes and total flight time, both influenced by organizational factors [8].

Occupational exposure data are primarily derived from the UNSCEAR Occupational Exposure Survey (Table 1). Approximately 90% of the personnel included in the 2010–2014 dataset are from the United States, followed by the United Kingdom, Germany, and France [8]. However, when compared with ICAO global estimates, these data represent only 30% of the worldwide workforce, limiting their representativeness. Despite this limitation, the average annual effective dose reported across the 2000–2014 UNSCEAR periods (2.7–2.8 mSv), aligns with ICAO global estimate. However, ICAO data are characterized by considerable uncertainty, with workforce estimates ranging from 570,000 to 990,000 individuals and the average annual effective doses between 1.5 to 4.6 mSv for the 2010–2014 period [8]. Substantial inter-country variability is observed, with average annual effective dose ranging from 1.03 mSv in Greece (2010–2014) to 4.00 mSv in Bulgaria (1990–1994). Even within a single country, such as the United States, the average annual dose remained stable at 3.07 mSv over the period 2000–2014 despite a 12% reduction in workforce, suggesting that differences in work allocation and organizational practices may contribute to exposure variability.

Variability in annual effective dose is influenced by latitude and operational factors, including working hours limits and definition of short-, medium-, and long-haul flights. Average annual flight time is approximately 600 h in Europe and 900 h in the United States [5], with regulatory limits of 900 h for crew members and 1000 h for pilots [8]. The definition of haul length varies between countries and airline companies, but it is estimated that, on average, 4% of worldwide flights last more than six hours, 13% from one to six hours and 83% less than one hour [8]. Notably, work conditions are regulated in collective labor agreements between airline operators and the labor unions of pilots and flight attendants, who can express individual preferences on route assignment within the constraints that the flight schedule requires [11].

Although UNSCEAR data do not differentiate pilots and cabin crew, available studies indicate exposure differences associated with role, gender, and career stage [8,11] While the majority of the aircrew are female (primarily cabin crew), male pilots and flight attendants tend to receive higher annual effective doses due to a greater likelihood of operating longer hauls routes [11,15]. Consistence with this, a German study reported higher average doses in cabin crew compared to cockpit crew, with values ranging from 2.15 mSv (female cabin crew) to 2.63 mSv (male cabin crew), and from 1.85 mSv (female cockpit crew) to 2.29 mSv (male cockpit crew) [16]. Career progression also influences exposure patterns: junior pilots typically operate short- and medium-haul flights, whereas senior officers and captains frequently fly long-haul routes. Family status further affects routes selection, particularly among female personnel, who may adjust flight patterns during different life stages. Male

flight attendants represent one of the most exposed subgroups, as they are more likely to select long-haul routes throughout their careers [11]. These findings highlight the interaction between environmental factors (e.g., altitude and latitude), operational variables (e.g., flight routes and schedules), and resulting occupational exposure, as conceptualized in the analytical framework adopted in this review. In addition, this variability underscores that, unlike most occupational radiation settings, exposure in aviation is largely driven by operational constraints rather than controllable environmental conditions.

Table 1. Occupational exposure of aircrew to cosmic ionizing radiation by country and period (adapted from UNSCEAR 2021 Report [8]).

Country	Period	Number of Workers (Thousands)	Average Annual Effective Dose (mSv)
Belgium	2013	3.3	1.37
Bulgaria	1990–1994	1.4	4.00
Czechia	1995–1999	1.0	1.52
	2000–2002	1.1	1.28
Denmark	2000–2004	3.7	1.99
	2005–2009	4.3	2.14
	2010–2014	4.3	2.01
Finland	1990–1994	1.9	1.96
	1995–1999	1.8	2.11
	2000–2004	2.5	1.75
	2005–2009	3.4	2.09
	2010–2014	3.6	2.38
France	2005–2009	20.1	2.20
	2010–2014	20.2	1.88
Germany	2004	28.2	1.40
	2005–2009	33.5	2.26
	2010–2014	38.6	2.06
Greece	2010–2014	1.5	1.03
Iceland	2005–2009	1.0	2.14
	2010–2014	1.6	1.85
Lithuania	2002	0.2	1.50
Netherlands	2001–2002	12.5	1.30
Slovenia	2010–2014	0.2	1.09
United Kingdom	1991	24.0	2.08
	2000–2004	39.9	2.40
	2005–2009	39.9	2.40
	2010–2014	39.9	2.40
United States	2003–2004	183.7	3.07
	2005–2009	174.1	3.07
	2010–2014	160.8	3.07
Total (reported countries)	1990–1994	27.3	2.15
	1995–1999	2.8	1.90
	2000–2004	294	2.68
	2005–2009	299	2.78
	2010–2014	293	2.68
Worldwide ^a	2000–2004	450	2.7
	2005–2009	600	2.8
	2010–2014	750	2.7

^a NB: International Civil Aviation Organization estimates.

3.2. Astronauts' Exposure

Spaceflight exposes astronauts to multiple hazards, including space radiation, altered gravity, confinement and isolation within hostile and closed environment far from Earth. It is conventionally defined as occurring above the Karman line, at approximately 100 km above sea level, where the atmosphere becomes too thin to sustain conventional aircraft flight [17].

The radiation field above typical aviation altitudes differs substantially in both composition and intensity. While low-energy SCR and GCR are partially shielded by the Earth's atmosphere and geomagnetic field, high-energy particles combined with secondary radiation generated by interactions with spacecraft structure cannot be fully shielded. Beyond the protective effects of the atmosphere and magnetosphere, astronauts are progressively exposed to increasing levels of GCR and SCR. In crewed spaceflights, radiation exposure varies according to mission profile, as summarized in Table 2, which reports mission duration, equivalent dose rate, and total equivalent dose for representative scenarios, Low-Earth Orbit (LEO), cis-lunar space, and planetary missions.

These estimates generally exclude large Solar Particle Events (SPEs), which are unpredictable and may significantly increase radiation exposure, potentially leading to deterministic effects such as skin injuries and/or acute radiation syndrome [5,7].

The International Space Station (ISS) orbiting at around 400 km altitude, remains partially protected by the magnetosphere, particularly at lower orbital inclinations. However, it traverses regions of enhanced radiations, including the Van Allen belts. Charged particles entering the magnetosphere near the poles may become trapped and form radiation belts with secondary protons in the inner belt representing a major contributor to astronaut exposure. The ISS intersects the South Atlantic Anomaly, a region where the inner belt is closer to Earth due to geomagnetic field asymmetry. Although passage through this region accounts for less than 10% of orbital time (typically ~15 min per orbit), it may contribute up to the 40% of the total daily equivalent dose measured aboard spacecrafts [9,18]. Under solar minimum conditions, measurement aboard the ISS, over a 168-day mission indicate a total dose equivalent of approximately 106 mSv, corresponding to an average of ~0.6 mSv/day [18,19] (Table 2). Across a cohort of 336 NASA astronauts the mean total absorbed dose of 16.8 mGy (standard deviation 23.6 mGy) [8], with reported daily effective dose rates ranging 0.2–0.5 mSv/day [20]. Additional studies combining physical dosimetry with biological markers (e.g., chromosome aberration) have reported average effective dose of approximately 72 mSv over six-months ISS missions [21].

In interplanetary and planetary missions, radiation exposure increases significantly due to the absence of geomagnetic shielding. Astronauts are directly exposed to primary GCR and SCR, as well as secondary radiation generated within spacecraft materials, particularly during SPEs [22,23]. Historical data from the Apollo missions (1–13 days) indicate relatively low total absorbed radiation doses (1.6 to 11.4 mGy) [8] primarily due to short mission duration. In planetary missions, CIR exposure depends on local atmosphere and magnetic shielding. The Moon lacks both, exposing astronauts to primary and secondary radiations, with protection limited to engineered shielding [24,25].

Measurement from the Chinese Lunar Lander Neutron and Dosimetry experiments indicate an average equivalent dose of 1.37 mSv/day over 21 days [24] (Table 2). Similarly, during the uncrewed Artemis I mission equivalent dose rates within the Orion capsule ranged between 0.96 to 1.24 mSv/day, with total mission equivalent doses varying from 26.7 to 35.4 mSv [26] (Table 2).

A trip to Mars would expose astronauts to significantly higher doses, as the planet lacks a global magnetic field, solar modulation decreases with distance from the Sun and deep space travelers would not benefit from the shielding provided by the mass of large planetary bodies. In addition, Mars has a thin atmosphere (2 orders of magnitude less atmospheric depth than Earth), therefore humans would be exposed to GCR, secondary particles generated by the interactions with nuclei in the atmosphere and in the soil, and SPEs [23]. During the Mars Science Laboratory (MSL) mission (cruise duration of 253 days), the Radiation Assessment Detector installed in the rover Curiosity measured a free space equivalent dose of 1.58 ± 0.22 mSv/day [27,28], with an overall equivalent dose of ~405 mSv during the cruise phase. On the Martian surface, an average GCR dose-equivalent rate of 0.64 ± 0.12 mSv/day was yielded over the first 300 sols (i.e., Martian days, corresponding to ~308 days) [29] (Table 2).

Table 2. Astronauts' exposure to cosmic ionizing radiation.

Mission Type	Cruise Duration (days)	Equivalent Dose Rate (mSv/day)	Equivalent Dose (mSv)	References
LEO (ISS)	168	0.6	106	[18,19]
Lunar free space	25	0.96–1.24	26.7–35.4	[26]
Lunar surface ^a	21	1.37	~28.8	[24]
Mars free space	253	1.58 ± 0.22	~405	[28]
Mars surface	~308	0.64 ± 0.12	~192	[29]

^a GCR dose equivalent rate of $(5.7 \pm 1.06) \times 10^{-2}$ mSv/hour [24]. Note: only LEO missions are derived from crewed missions, while others from uncrewed missions. Where available, uncertainties and ranges in dose rates are reported as provided by the original literature. Total mission equivalent doses that were not explicitly reported were calculated by multiplying the measured doses by the mission duration and are indicated with the ~symbol.

To further estimate astronauts' radiation exposure during a Mars mission, various models have been developed, typically assuming a 180-day one-way transit and a 500-day surface stay as for the scenarios evaluated by The Mars Design Reference Architecture [30]. In the model, developed assuming the measured GCR-dose rate on Martian surface (i.e., the MSL RAD dose rate) together with the free-space dose equivalent measured onboard of Orion spacecraft during the Artemis I mission [26], different transit durations and time spent on the Martian surface have been used. The lowest modeled mission exposure was approximately 530 mSv when selecting the

most shielded area (representative of the crew module) and the shortest mission duration (560-days total trip time, including fuel-efficient 530-days long transit and 30-days short surface stay) [26].

To highlight the effect of shielding, the highest modeled mission exposure (770 mSv) would occur when selecting the least shielded area of the spacecraft in an 860-days mission scenario (360 days of transit and 500 days on the Martian surface). Under the same mission conditions, selecting the most shielded location would reduce the total mission exposure to approximately 660 mSv, corresponding to a reduction of up to 14% [26]. Although mission productivity would be amplified in a 700-days surface stay scenario as compared to the 500-days scenario, the total mission exposure would still range from 640 mSv in the least shielded area to 690 mSv in the most shielded area, even when adopting the shortest 200-days transit time and an overall 900-days total mission duration [26]. Overall, these results suggest that, although radiation exposure in deep space can be significantly higher due to the limited shielding provided by spacecraft, employing nuclear propulsion to reduce transit time does not significantly reduce the overall crew dose [26].

Moreover, it should be noted that Solar Particle Events (SPEs), not specifically considered in the modelled estimates, could deliver an additional dose of approximately 200–300 mSv per event. While reliable forecasting systems for SPEs are not yet fully available, mission architectures that account for the solar cycle phase and the heliocentric distance along the trajectory would contribute to reducing the cumulative radiation dose experienced by astronauts [26]. In astronauts, the interplay between environmental radiation conditions, mission-specific operational factors, and resulting occupational exposure is amplified compared to aviation, reinforcing the relevance of the proposed analytical framework.

3.3. Occupational Health Considerations

The biological effects of cosmic radiation are a primary concern for both aircrew and astronauts. Radiation interacts with biological tissues by transferring energy to cells, causing structural damage that may result in cell death or genetic alterations. When cellular damage exceeds the regenerative capacity of tissues, functional impairment and clinical manifestations may occur. These effects, known as a deterministic effect or tissue reactions, occur above specific dose threshold and increase with dose [6,31]. In contrast, stochastic effects arise from radiation-induced damage to cellular DNA that is not adequately repaired or eliminated, potentially leading to carcinogenesis. These effects are described using a Linear-Non-Threshold model (LNT-model), which assumes that cancer risk increases proportionally with dose without threshold [32,33]. Ionizing radiation exposure has been associated with increased risk in leukemia, lung cancer, breast cancer, gastrointestinal tract cancer, skin cancer and thyroid cancer [6,33]. The biological impact of radiation is strongly influenced by radiation quality. High Linear Energy Transfer (LET) particle such as neutrons, alpha particles, and heavy ions, produce greater biological damage per unit dose than low-LET radiation (e.g., X-rays and gamma rays), due to their higher energy deposition along particle tracks [6].

At the molecular and cellular level, radiation exposure induce oxidative stress, direct and indirect DNA damage, mitochondrial dysregulation, chromatin remodeling, and alterations in telomere dynamics [6,32,34]. Rapidly proliferating tissues with an elevated cellular turnover, such as bone marrow, the gonads or the gastrointestinal mucosal layer, are more sensitive to radiation-induced apoptosis, thus to deterministic effects [35]. Also disruptions in the neuronal, cardiac and renal tissues have been observed with GCR exposure [34]. Radiation is also a recognized teratogen, capable of causing fetal death and congenital malformations at doses exceeding approximately 100 mGy [4]. Acute high-dose may results in Acute Radiation Syndrome (ARS), with severity dependent on absorbed dose, with individual susceptibility [6].

Understanding the effect of CIR on both aircrew and astronauts is complex, as radiation is not the only hazard and is difficult to be directly measured. Moreover, these workers undergo thorough medical examinations before employment to exclude individuals with relevant health problems [35]. Therefore, the evaluation of the radiation health effects in these occupational groups may result in an underestimation of the real associations (i.e., healthy worker bias).

Amongst tissue reactions, crystalline lens is one of the most radiosensitive tissue [36]. Both aircrew and astronauts consistently show an increased prevalence of cortical sub-capsular cataract compared to unexposed/lower exposed populations [31,37–40].

Regarding stochastic effects, cancer is the primary long-term risk associated with CIR exposure. In aircrew chronic exposure to low doses of neutrons, with an overall mix of high- and low-LET particles has been associated with overall cancer incidence comparable to the general population, although mortality is often lower, likely reflecting selection effects. Some studies suggest increased risks of melanoma, non-melanoma skin cancers, and

breast cancer, although confounding factors such as ultraviolet radiation exposure, circadian disruption, and reproductive history complicate interpretation [10,37–41].

Specifically looking at astronauts, it should be considered that the understanding of the biological impact of high-LET radiation exposure is still based on animal models [32,42]. Despite this, NASA has developed a GCR simulator to approximate the GCR field experienced in deep space, thus further investigations are expected in the future [43]. Data available on 338 astronauts selected to the US Astronauts Corps between 1959 and 2013 suggests that their occupational exposure did not substantially increase cancer incidence and mortality, in comparison to the US general population, with the main exception of melanoma skin cancer. Considering 70% of the cohort was a licensed pilot, the increased melanoma incidence was explained by the predominant exposure to non-ionizing Ultraviolet A (UVA) radiation [44]. Although epidemiological evidence linking CIR exposure to cancer remains limited and considering that cancer risk projections on humans are nowadays still highly uncertain, predictions in multiple ISS missions suggest a major GCR exposure role in cancer induction [45]. From an occupational health perspective, these findings support the need for structured exposure monitoring systems, targeted worker education, and risk communication strategies tailored to both aircrew and astronauts. For aircrew, implementation of validated dose assessment models and optimization of flight schedules remain key preventive measures. For astronauts and spaceflight participants, individualized risk assessment, enhanced medical surveillance, and clear informed consent processes are essential, particularly in the context of commercial missions. Employers and mission operators bear increasing responsibility in ensuring transparent risk communication, compliance with evolving regulatory frameworks, and the development of standardized health protection protocols.

3.3.1. The Radioprotection Framework in Civil Aviation

The radioprotection framework is designed to protect human health by preventing deterministic effects and reducing the probability of stochastic effects to a level that is As Low As Reasonably Achievable (ALARA) [4]. For effective doses up to 100 mSv, whether delivered as a single dose or accumulated over time, no clinically tissues reactions are expected; however, the probability of stochastic effects increases linearly with the dose. This dose-response model, known as LNT-model, is widely accepted as the most practical approach for managing radiation-related risks [4]. Moreover, above tissue-specific thresholds deterministic effects may occur, being the result of tissue reactions induced by the radiation in the exposed biological system [4,31].

According to ICRP guidelines [2,4,39], occupational exposure occurs when the reference level for the general public (1 mSv/year) is likely to be exceeded. As shown in Table 1, aircrew in European countries and in the USA exceed this threshold on average and are therefore classified as occupationally exposed workers. The Council directive 2013/59/EURATOM further categorizes Category B workers (annual effective dose between 1 and 6 mSv/year) and category A (annual effective dose higher than 6 mSv/year), the latter requiring more stringent protection measures and health surveillance. The annual effective dose is set at 20 mSv/year averaged over 5 years, with a maximum of 50 mSv permitted in a single year under special circumstances [1]. According to data shown in Table 1, aircrew members in European countries generally are classified within the category B and are therefore subject to standard protection measures. The U.S. FAA adopts the ICRP and NCRP recommendations, and aircrew are considered adequately protected under current occupational standards [7]. Despite exposure levels remain well below the regulatory limits, the chronic nature of the CIR exposure continues to raise concerns regarding potential long-term effects.

A key challenge in aviation is the limited ability to directly control or reduce radiation exposure, as it depends on external environmental factors and operational constraints. For an adequate implementation of a protection strategy, ICRP suggests actions on flight schedules, limiting the exposure of the personnel by considering flight time and route selection. The airline management must inform the aircraft crew and assess the annual effective dose of each member, using validated algorithms, if personal dosimetry is not reliable [5]. Specific medical examinations within health surveillance programs related to radiation exposure are not strictly recommended for aircrew personnel according to the exposure levels currently identified (Table 1). Nevertheless, occupational health programs should include general medical examinations, risk communication and counselling interventions provided by the occupational physicians of the flight companies, also aimed at identifying possible conditions of susceptibility to the radiation risk. Relevant international guidance on the protection of workers exposed to IR, including occupational risk assessment, exposure monitoring, and preventive measures such as worker training and health surveillance, is available from the IAEA [46] and the International Labour Organization (ILO) [47]. However, these documents were published several years ago and provide only limited specific guidance for workers employed in civil aviation. As a general principle, workers should be informed about the nature and sources of potential health risks. This principle clearly applies to aircrew with respect to IR exposure. They should

be made aware that, unlike other categories of IR-exposed workers, personal monitoring is not scientifically recommended for them. Instead, their exposure is assessed using standardized and validated procedures and algorithms. The aim is to ensure adequate health protection in accordance with radiation protection principles and to identify any need for additional measures when relevant exposure levels may be exceeded. Among such measures, health surveillance should also be considered. According to the ICRP, aircraft crew already undergo routine medical examinations for reasons unrelated to radiation protection; therefore, additional medical examinations specifically for IR exposure are not generally required [5]. Nevertheless, in specific cases—primarily on an individual basis and following medical evaluation targeted health surveillance programs related to IR exposure for aircrew may be implemented. In line with the International Code of Ethics for Occupational Health Professionals issued by the International Commission on Occupational Health (ICOH), any additional examinations should be “chosen for their validity and relevance for the protection of the health of the worker concerned, with due regard to their sensitivity, specificity, and predictive value.” Screening tests or investigations that are unreliable or lack sufficient predictive value in relation to job requirements should not be used [48].

3.3.2. Radioprotection Framework in Astronauts

The ICRP system is based on population-level protection, conservative dose limits, and the principle of justification and optimization, assuming relatively well-characterized radiation types and large exposed populations. In contrast, Space Agencies operate in a context of high uncertainty, low statistical power, and mission-driven constraints, where individual risk assessment becomes central. During the preflight phase, each astronaut undergoes a full screening that consists in a general medical evaluation integrated with imaging and laboratory exams, along with training sessions on first-aid interventions possibly needed in case of any emergency occurring during spaceflights [49,50]. Following spaceflight, it is recommended that astronauts undergo occupational health surveillance for the detection of any health issues related to space travel [49]. Considering CIR assessment, crew exposure history must be assembled prior to spaceflight, while mission exposure and the related risks need to be predicted based on planned mission activities, with the aim to minimize CIR exposure according to the ALARA principle. During spaceflight, radiation exposure and health risks should be evaluated, and possibly forecasted. Moreover, exposure from each mission and accumulated exposure must be used for health risk assessment and recorded on an individual basis [9,51]. Radiation monitoring is typically performed through a combination of active and passive dosimeters and environmental devices onboard spacecrafts, coupled with computational models [28,52].

Significant differences persist among models in both the metrics adopted and the methodologies used for dose reconstruction and risk estimations across Space Agencies. For instance, NASA has adopted a career limit of approximately 0.6 Sv, ensuring that the Risk of Exposure-Induced Death (REID) does not exceed 3%. In contrast, the European Space Agency (ESA), along with the Canadian Space Agency (CSA) and the Russian Space Agency (RSA), maintains a higher career limit of 1 Sv, while the Japan Aerospace Exploration Agency (JAXA) adopts intermediate values in the range of 0.5–1 Sv, depending on sex and age [20]. These discrepancies are not merely numerical but stem from fundamentally different radioprotection philosophies, ranging from risk-based models (NASA) to more operational or dose-base approaches (ESA, RSA), as well as hybrid and model-driven frameworks (JAXA) [20,53].

Although typical six-months ISS missions result in doses well below these career limits, as shown in Table 2, the lack of consistency in dosimetric quantities and risk models complicates direct comparison between agencies and raises questions regarding the equivalence of protection levels. This issue becomes more critical when extrapolating to missions beyond LEO [54]. Lunar missions, including the Artemis program, are expected to result in higher exposures due to reduced geomagnetic shielding, yet still remain nominally within current agency limits. [26,54]. However, for Mars missions, radiation exposure becomes a major limiting factor, as deep-space transit and surface operations entail continuous exposure to CIR with minimal shielding, leading to estimated cumulative doses in the range of 530–770 mSv, with potentially significant additional contributions from SPEs, especially for trajectories approaching the inner solar system. Epidemiological evidence suggests that exposure in this range is associated with both stochastic and deterministic effects and increased risks of radiation induced mortality and morbidity, posing a significant challenge to the feasibility of long-duration missions under current protection standards. Radioprotection strategies for interplanetary missions must therefore rely heavily on mission design optimization, advanced shielding solutions, real-time monitoring and pharmacological countermeasures [50], rather than strict adherence to predefined limits. This shift highlights a fundamental limitation of existing frameworks, which were largely developed for LEO conditions and may not be directly transferable to deep-space exploration. Under these conditions, the applicability of current dose limits becomes questionable, as the lack of

harmonization leads to relevant inconsistencies when comparing protection standards across Agencies [54]. This indicates that current limits are strongly model-dependent, thus what is considered an acceptable level of risk varies quantitatively and conceptually, especially for transient but dangerous situations such as SPEs, thus raising important ethical and policy questions. The absence of a unified framework complicates the definition of acceptable risk thresholds and suggests that future radiation protection systems may need to move beyond fixed limits toward adaptive, mission-specific risk management strategies. It is noted that also non-technical factors confound consensus on exposure limits, as cultural differences or national interests inherently bring differences in the cost/benefit evaluation of a mission [20].

The integration of environmental, operational and occupational dimensions allows the delineation of distinct exposure profiles across aircrew and astronauts, as summarized in Table 3.

Table 3. Overview of occupational exposure to cosmic ionizing radiation in aircrew and astronauts.

Dimensions	Aircrew	Astronauts	Astronauts
	Typical Altitude (8–12 km)	Low-Earth Orbit (400 km)	Deep Space
Environmental			
Radiation field	Mixed (> low-LET)	Mixed (>high-LET)	High-LET predominant
Shielding	High shielding	Partial shielding	Minimal shielding
Operational			
Exposure pattern	Chronic, low dose	Subacute	Chronic + SPE peaks
Determinants	Flight time, routes	Mission duration, orbit	Mission design, transit
Protection strategies	Flight scheduling (ALARA)	Spacecraft shielding Dosimetry	Spacecraft shielding Mission design SPE mitigation strategies
Occupational			
Typical exposure	Effective dose 1–5 mSv/year	Equivalent dose 0.2–0.6 mSv/day	Equivalent dose 0.6–1.6 mSv/day
Health risks	Inconclusive cancer associations	Cataracts; limited cancer data	Limited human evidence
Regulatory framework	Standard occupational limits	Agency-specific career limits	Not harmonized High uncertainty in risk models

This structured comparison highlights not only the differences in exposure scenarios, but also the increasing complexity of radioprotection frameworks, which becomes even more relevant in the context of emerging commercial spaceflight activities. In this evolving scenario, renewed human space exploration programs, including those led by emerging private companies, are expected to increase the number of workers potentially exposed to CIR, as well as the number of civilian astronauts (also referred to as spaceflight participants [55]). In the context of private companies, as opposed to national governmental agencies, the health and safety of employed workers must be carefully addressed, without the possibility of treating them as individuals subject to authorized exceptional exposures (e.g., for military or research purposes) justified on the grounds of *raison d'état*.

The rapid expansion of access to space across an increasing number of countries is creating new commercial opportunities, including suborbital flights, missions to the International Space Station, and even deep-space travel. At the same time, it introduces novel challenges for radiation protection, as cumulative career exposures may occur outside traditional agency frameworks, and regulatory and monitoring protocols for private astronauts are not yet standardized.

Employers in the private sector are required to comply with national legislation governing the protection of workers' health and safety; this obligation clearly extends to IR exposure and to astronauts. However, at this early stage, no widely shared best practices or recognized guidelines are specifically available for this emerging sector and its associated occupationally exposed groups. It should also be recalled that, according to the Federal Aviation Administration, spaceflight participants must be informed of all hazards and risks that “could result in serious injury, death, disability, or total or partial loss of physical or mental function, as well as unknown risks” [55]. Moreover, spaceflight participants represent a novel IR-exposed cohort. Unlike traditional professional astronauts—typically selected as healthy, relatively young individuals and predominantly male—this group may include individuals with a broader age range and a higher prevalence of pre-existing medical conditions [56].

A key distinction emerges when comparing terrestrial and spaceflight radioprotection frameworks. The ICRP system is grounded in population-level protection and conservative dose limits based on the linear no-threshold model, whereas NASA adopts a risk-based approach centered on permissible lifetime cancer risk (REID), allowing

for higher exposures in the context of mission objectives. ESA and other agencies adopt intermediate strategies, reflecting both precautionary principles and operational constraints. These differences highlight an underlying tension between occupational health protection and mission-driven risk acceptance. While aircrew operate within clearly defined regulatory thresholds, astronauts are subject to individualized risk trade-offs, often exceeding standard occupational limits. This divergence raises important ethical and policy questions, particularly in the context of emerging commercial human spaceflight, where regulatory responsibility, informed consent, and acceptable risk thresholds remain insufficiently harmonized.

4. Conclusions and Emerging Challenges

Charged particles coming from the Sun and the galaxy are a source of cosmic ionizing radiation that impacts differently on both aircrew and astronauts. The Earth is protected by its atmosphere and geomagnetic field, which offer higher shielding at aviation altitude rather than at orbital or deep space flights. Therefore, astronauts are more exposed to cosmic ionizing radiation than aircrew, quantitatively and qualitatively.

Aircrew are considered occupationally exposed, as the average annual effective dose exceeds 1 mSv/year. Notably, chronic low-dose exposure in aircrew is associated with stochastic effects, such as cancer, yet epidemiological studies show a healthy worker effect that may mask subtle long-term impacts. This highlights the ethical need for ALARA strategies through work organization, since adjusting the flight route mix and the annual flight time directly influences individual doses. This approach allows employers to fulfill their duty to protect workers within the established regulatory standard.

For astronauts, occupational health considerations arise from the unique radiation field in space and the substantial uncertainties in risk models, due to the poor representation of space radiation by terrestrial analogs and the limited availability of human data. Consequently, the selection of career dose limits should be interpreted as a trade-off between mission feasibility and the mitigation of long-term health risks, as excessively stringent limits would significantly constrain exploration-class missions. These limits reflect the agency-specific risk tolerance, as well as distinct risk cultures and political accountability frameworks.

Continuous refinement of monitoring systems, exposure models, and radiological protection strategies remains essential to safeguard the health and safety of both aircrew and astronauts, as well as civilian spaceflight participants, including those of the recently emerging private companies. While the existing radioprotection framework is considered sufficient for aviation, LEO and lunar missions, based on current evidence, Mars missions and emerging commercial exploration will need further optimization. The evolving landscape of human spaceflight calls for advancements in radiobiology and international harmonization of radioprotection standards, extended to non-governmental activities.

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Abbreviations

ALARA	As Low as Reasonably Achievable
CIR	Cosmic Ionizing Radiation
CSA	Canadian Space Agency
IAEA	International Atomic Energy Agency
ICAO	International Civil Aviation Organization
ICRP	International Commission on Radiological Protection
ILO	International Labour Organization
ISS	International Space Station
ENAC	Ente Nazionale per l'Aviazione Civile
ESA	European Space Agency
FAA	Federal Aviation Administration
GCR	Galactic Cosmic Radiation
JAXA	Japan Aerospace Exploration Agency
NASA	National Aeronautics and Space Administration
NCRP	National Council of Radiation Protection and Measurements
LEO	Low-Earth Orbit
LET	Linear Energy Transfer
LNT	Linear-No-Threshold (model)
MSL	Mars Science Laboratory
REID	Risk of Exposure-Induced Death
RSA	Russian Space Agency
SCR	Solar Cosmic Radiation
SPE	Solar Particle Event
Sv	Sievert
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

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