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Levels of radiation exposure near AOS and OSF

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Abstract

Levels of radiation exposure in Chilean altiplano primarily due to cosmic rays were measured with pocket gamma ray dosimeters and a handy neutron rem counter. Comparison data were also taken at Antofagasta, Santiago, Mitaka, and on board the aircrafts to/from the site. Significant enhancement of dose rates was found at the ALMA site: Measured gamma ray dose rate (including $\sim 0.45\,\mathrm{mSv\,yr^{-1}}$ contribution of terrestrial gamma ray) was $3.14\,\mathrm{mSv\,yr^{-1}}$ at Pampa La Bola, and $1.70\,\mathrm{mSv\,yr^{-1}}$ at San Pedro de Atacama, respectively, whereas it was $0.99\,\mathrm{mSv\,yr^{-1}}$ at Santiago. As for the neutron component, altitude dependence is severer: Measured neutron dose rates were $0.80\,\mathrm{mSv\,yr^{-1}}$ at Pampa La Bola, and $0.25\,\mathrm{mSv\,yr^{-1}}$ at San Pedro de Atacama, respectively, whereas it was $0.01\,\mathrm{mSv\,yr^{-1}}$ at Santiago. These values are even higher than world average dose rates at comparable altitudes, probably reflecting enhancement of incoming primary cosmic rays near the South Atlantic Anomaly. After correction for the effects of solar activity and indoor shielding, we estimate the occupational exposure of an 8–6 turno employee to be $2.0\,\mathrm{mSv\,yr^{-1}}$, which exceeds that of a typical worker engaged in nuclear fuel cycle.

1 Introduction

1.1 Enhanced secondary cosmic rays at high altitude

We are continuously exposed to ionizing radiation. The natural sources of that exposure include galactic and solar cosmic rays, and terrestrial radio nuclides that occur in the Earth's crust, in building materials and in air, water and foods and in the human body itself. Some of the exposures are fairly constant and uniform for all individuals everywhere, for example, the dose from ingestion of ^{40}K in foods. Other exposures vary widely depending on location. Cosmic rays, for example, are more intense at higher altitudes. Located at very high altitude, higher radiation exposure due to cosmic rays is expected at the ALMA site. In fact, annual dose of an aircrew is estimated to be around $3.0\,\mathrm{mSv\,yr^{-1}}$, which is about 8 times the world average annual dose due to cosmic rays (see, Table 1) [1], and occupational dose due to enhanced cosmic rays is of recent concern.

Another important aspect for ALMA is the effects of enhanced cosmic ray dose rate on instruments: enhanced total ionizing dose (TID), which is a cumulative long-term degradation of the device exposed to ionizing radiation, and enhanced rate of single event effects (SEEs), which are individual events which occur when a single incident ionizing particle deposits enough energy to cause an effect in a device, due to enhanced cosmic ray dose rate. There are many device conditions and failure modes due to SEE, depending on the incident particle and the specific device, but may be classified into soft errors and hard errors. Soft errors are nondestructive to the device and may appear as a bit flip in a memory cell or latch, or as transients occurring on the output of an I/O, logic, or other support circuit. Also included are conditions that cause a device to interrupt normal operations and either perform incorrectly or halt. Hard errors may be (but are not necessarily) physically destructive to the device, but are permanent functional effects. Unlike TID degradation, SEE rates are not evaluated in terms of a time or dose until failure, but a probability that an SEE will occur within a known span of time. Such effects of enhanced cosmic rays on ALMA instruments are, however, beyond the scope of this brief report and will be presented elsewhere [2].

1.2 The South Atlantic Anomaly (SAA)

There is an additional factor that may locally enhance the cosmic ray intensity near the ALMA site. Earth is surrounded by a close-to-spherical magnetic field, the magnetosphere. It protects us from cosmic rays by deflecting or by capturing them in the Van Allen Belts. At a certain location over the South Atlantic Ocean, however, the shielding effect of the magnetosphere is not quite spherical but shows a pothole, which is believed to be a result of the eccentric displacement of the center of the magnetic field from the geographical center of the Earth (by about 400 km) as well as the displacement between the magnetic and geographic poles of the Earth. This oddity, called the South Atlantic Anomaly (SAA) becomes important for spacecrafts with orbits tilted between 35° and 60° against the Earth's equator and having altitudes of a few hundred kilometers, because spacecrafts in those orbits periodically pass through that zone of reduced natural shielding and thus spend a few minutes during each passage exposed to higher particle flux than outside it. Hence existence of the SAA may also cause local enhancement of secondary cosmic ray intensity in the lower atmosphere of this region in which the ALMA site is included.

1.3 Components of cosmic rays and quantification of their impacts

Cosmic rays are composed of several components: high energy photons, electrons, protons, neutrons, and muons. Components other then neutrons are classified as ionizing components. These components have different levels of impacts on exposed material.

The basic quantity used to express the exposure of material by radiation is the absorbed dose, for which the unit is Gy (gray: $1\,\mathrm{Gy} = 1\,\mathrm{J\,kg^{-1}}$). However, the biological effects per unit of absorbed dose vary with the type of radiation and the part of the body exposed. To take account of those variations, a weighted quantity called "effective dose" is used, for which the unit is Sv (sievert). The effective dose is calculated by,

$$\text{(effective dose)} = \text{(absorbed dose)} \times \text{(radiation weighting factor)}, \tag{1}$$

where the radiation weighting factor is 1.0 for photons, electrons and muons, whereas it ranges 5–20 for neutrons depending on their energy. In reporting levels of human exposure, the effective dose is widely used.

2 Measurements

2.1 Gamma ray dose measurements

Measurements of ground-level radiation exposure due to gamma ray were carried out at Pampa La Bola (alt. = 4800 m, near the AOS) and San Pedro de Atacama (alt. = 2450 m, near the OSF) during the period of 2003 January 9–19. Solar activity was near the maximum of the 11-yr cycle during the measurements. Two Polimaster PM-1621 dosimeters [3] were used to record the absorbed dose. The detector of PM-1621 was a Geiger-Müller tube with a sensitivity range from 10 keV to 20 MeV and had a dose rate measurement range from $0.1\,\mu\mathrm{Sv\,hr^{-1}}$ to $0.1\,\mathrm{Sv\,hr^{-1}}$. Energy response relative to 0.662 MeV (^{137}Cs) within the energy range was specified to be $< \pm 30\%$. The specified accuracy was $< \pm 15\%$. Cumulative dose was recorded manually resulting in heterogeneous time resolution.

Reference data were collected at Mitaka on the top of a three-storied building from 2002 December 27 to 2003 January 5 (JST), and also on the first story of another three-storied building from 2003 January 5 to January 7 (JST). Data were also collected during the air travel to/from the site, from Narita to Dallas/Fort Worth (AA-060; 10.9 hr flight at cruising altitudes from 11278 m or 37000 ft to 12496 m or 41000 ft) from Dallas/Fort Worth to Santiago (AA-945; 8.8 hr flight at cruising altitude of 10668 m or 35000 ft), from Santiago to Calama via Antofagasta (LA-354; 1.6+0.4 hr flight), from Calama to Santiago via Antofagasta (LA-343; 0.4+1.4 hr flight), from Santiago to Miami (AA-912; 8.0 hr flight), and from Miami to Tokyo via Chicago (AA-153; 2.9+12.4 hr flight). During the AA-060 and AA-153 flight, the altitude of the aircraft was measured with the navigation monitor of the Boeing 777 aircraft. Because of rapid ascending and descending of aircrafts, however, the values during ascending phase may significantly underestimate true values and vice versa. Since location within an aircraft does not affect the exposure level by more than $\pm 10\%$ [4], the data taken at window and isle seats were not corrected for different indoor shielding factors.

Relative calibration of these instruments was checked by side-by-side measurements aboard the aircrafts. These two instruments were occasionally changed so that instrumental error can be minimized.

2.2 Neutron dose measurements

Measurements of ground-level radiation exposure due to neutron component were carried out at Pampa La Bola (alt. = 4800 m, near the AOS) and San Pedro de Atacama (alt. = 2450 m, near the OSF) during the period of 2003 January 9–19, as well as during the air travel to/from the site, with a Fuji Electric NSN10014 neutron rem counter. The detector of NSN10014 was a spherical ^{3}He proportional counter covered in spherical polyethylene and having a neutron energy range from 0.025 eV to 8 MeV with an energy response in accordance with ICRP 51 standard [5]. The detector had a minimum dose rate measurement range of $0.001\,\mu\mathrm{Sv\,hr^{-1}}$. The ground measurements were in integration mode — cumulative dose was recorded manually resulting in heterogeneous time resolution — while the onboard measurements were in survey mode with time resolutions ranging from 1 to 60 s depending on the dose rate.

2.3 Satellite data

To evaluate incoming primary cosmic ray density, we used satellite data of spatial distribution of neutron (chiefly formed through interaction of primary cosmic ray particles with walls of the International Space Station) measured with the Bonner Ball Neutron Detector (BBND) [6, 7] aboard the International Space Station (ISS) at an orbit about 400 km above the ground. Since the tilt of the orbit of the ISS is 51.65°, the data were limited to the latitude range lower than this. The data used here are those taken during 2001 March 23–November 14.

The BBND measures neutron radiation in an energy range from thermal to 15 MeV via a series of six ^{3}He sensors. In the center of each sensor, there is an identical ^{3}He proportional counter that contains ^{3}He at 6.1 atmospheres pressure in a stainless steel spherical shell. Three out of the six ^{3}He counters are covered in polyethylene moderators of different thicknesses, one is with a polyethylene moderator covered in a 1 mm thick Gd material to block thermal neutrons, one is covered in Gd material without a polyethylene moderator, and one is uncovered ^{3}He detector. When neutrons pass through the shell, a series of reactions initiated by $^3\mathrm{He} + \mathrm{n} \rightarrow {}^3\mathrm{H} + \mathrm{p} + 764\,\mathrm{keV}$ occur, resulting in electrons that are collected onto the wire, and neutrons are measured as the electrical current running through the wire.

3 Global distribution of primary cosmic rays at low Earth orbits

Presented in Figure 1 is an image of the global distribution of dose equivalent rate due to neutrons with energy range from thermal to 15 MeV. Note that the measured neutrons are not only primary but mostly secondary neutrons produced by interaction of primary ionizing cosmic rays with the walls of the ISS. Since the tilt of the orbit of the ISS is 51.65°, the data were limited to the latitude range lower than this. It is clear from this figure that, except for very high geomagnetic latitude, most neutron activity takes place around the South Atlantic Anomaly (SAA). The ALMA site is located near the edge of the SAA, and the dose equivalent rate in the ISS traveling over the ALMA site was $7.6\,\mu\mathrm{Sv\,hr^{-1}}$, while that over Mitaka was $1.3\,\mu\mathrm{Sv\,hr^{-1}}$ (see, Table 2). It is thus concluded that, at low Earth orbits above the ALMA site, incoming primary cosmic ray is enhanced by a factor of 5.7 with respect to Mitaka.

4 Cosmic ray dose rates

4.1 Altitude dependence of gamma ray dose rate

The outdoor gamma ray dose rate at Mitaka was $0.093\,\mu\mathrm{Sv\,hr^{-1}}$ ($0.82\,\mathrm{mSv\,yr^{-1}}$) and the one at Santiago (alt. = 520 m) was $0.113\,\mu\mathrm{Sv\,hr^{-1}}$ ($0.99\,\mathrm{mSv\,yr^{-1}}$). By contrast, the outdoor gamma ray dose rates measured with the same dosimeters were significantly higher than the values measured at the lower altitudes, and were $0.358\,\mu\mathrm{Sv\,hr^{-1}}$ ($3.14\,\mathrm{mSv\,yr^{-1}}$) at Pampa La Bola and $0.194\,\mu\mathrm{Sv\,hr^{-1}}$ ($1.70\,\mathrm{mSv\,yr^{-1}}$) at San Pedro de Atacama, respectively. The difference between the value at Pampa La Bola and San Pedro de Atacama is not artifact due to instrumental calibration error, since the results of side-by-side measurements suggest that readings of these two identical dosimeters give consistent value within an error of 1%.

At altitudes of cruising aircrafts (alt. $\simeq$ 10000 m), measured gamma ray dose rates were even higher: The values ranged 1.4–3.1 $\mu\mathrm{Sv\,hr^{-1}}$ (12–27 $\mathrm{mSv\,yr^{-1}}$) as shown in Figure 2. Besides the dominating altitude dependence, there exists significant variation of dose rate with location on the Earth, as characterized by local minima near the equator and enhancement toward North America.

The above measured values of radiation exposure is plotted in Figure 3 as a function of altitude. Probable contamination by terrestrial gamma rays in Chile at a level of $0.051\,\mu\mathrm{Sv\,hr^{-1}}$ ($0.45\,\mathrm{mSv\,yr^{-1}}$) [9] is not subtracted in this plot. The trend found in Chilean altiplano seems to agree with that found from previous studies [8, 10]. By fitting the dose rate measured at the ALMA site with the standard curve for habitable altitude,

$$\dot{E}(z) = \dot{E}(0)\,[0.21\exp(-1.649z/\mathrm{km}) + 0.79\exp(0.4528z/\mathrm{km})]\,, \qquad (2)$$

with z being the altitude above the sea level and $\dot{E}(0)$ being the dose rate at sea level [11], the absolute value of the outdoor dose rate at sea level extrapolated from the results is $0.59 \pm 0.12\,\mathrm{mSv\,yr^{-1}}$. This value is 2.2 ± 0.4 times larger than the world average ($0.27\,\mathrm{mSv\,yr^{-1}}$ [1]), probably reflecting (but not fully) the enhancement of incoming primary cosmic rays near the SAA.

The effective gamma ray doses recorded during individual one-way flights were 23.9 μSv for Narita–Dallas/Fort Worth, 13.5 μSv for Dallas/Fort Worth–Santiago, and 1.9 μSv for Santiago–Antofagasta–Calama, 1.6 for Calama–Antofagasta–Santiago, 10.3 for Santiago–Miami, 5.7 for Miami–Chicago, and 27.8 for Chicago–Narita, respectively. Total gamma ray dose of these flights was 84.7 μSv. The above values should be multiplied by 1.4 to include neutron contribution (see, following subsection). These are systematically smaller by about 20% than the ones calculated with the CARI-6 software [12].

4.2 Altitude dependence of neutron dose rate

Altitude dependence of neutron dose rate is also shown in Figure 3. Measured neutron dose rates were $0.091\,\mu\mathrm{Sv\,hr^{-1}}$ ($0.80\,\mathrm{mSv\,yr^{-1}}$) at Pampa La Bola, $0.028\,\mu\mathrm{Sv\,hr^{-1}}$ ($0.25\,\mathrm{mSv\,yr^{-1}}$) at San Pedro de Atacama, $0.002\,\mu\mathrm{Sv\,hr^{-1}}$ ($0.02\,\mathrm{mSv\,yr^{-1}}$) at Antofagasta, $0.001\,\mathrm{mSv\,hr^{-1}}$ ($0.009\,\mathrm{mSv\,yr^{-1}}$) at Santiago, and 0.3–1.3 $\mu\mathrm{Sv\,hr^{-1}}$ (2.6–11 $\mathrm{mSv\,yr^{-1}}$) at altitudes of cruising aircrafts with the lowest value near the equator, respectively.

At high altitude, neutron dose rates were approximately 40% of corresponding gamma ray dose rates, whereas the contribution of the neutron component becomes negligible at sea level. These are consistent to the altitude dependence of the fractional contribution by components of cosmic rays [13].

4.3 Effects of solar activity

Effects of solar activity on cosmic ray intensity have been intensively studied [1]. According to previous studies, primary cosmic ray intensity correlates with solar activity for two reasons. Firstly, enhanced solar activity measures cosmic ray intensity of solar origin. This becomes most prominent when the Sun flares, and the cosmic ray intensity in pole regions may reach 4–16 times more than the value of calm cases [8]. On the contrary, enhanced solar magnetic field shields galactic low energy cosmic rays more effectively. As a result of balancing, cosmic ray intensity becomes slightly suppressed when the Sun is active.

Because of the limited term, sensitivity, and time resolution of the measurements, however, it is difficult to assess the effects of solar activity with the present data set. In this subsection, we thus try to estimate the long-term average of the cosmic ray dose rate in this area from records obtained in other regions on the Earth.

The measured period corresponded to solar maximum and thus the obtained values may be understood as lower limits to those expected for long-term average. By using the cosmic ray intensity monitored by the Climax Neutron Monitor at Climax (alt. = 3400 m), Colorado, USA (Figure 4) [14], we estimate that the long-term average is about 1.04 times larger than the measured values.

4.4 Indoor shielding

Although most of the gamma ray measurements at the sites were carried out under outdoor environments, the indoor dose rates may not differ much from the measured values: According to literatures, the indoor shielding factor of ionizing components range from close to 1.0 (almost no attenuation) for minimal vertical shielding such as a small wooden house, to 0.4 (60% attenuation) for lower stories of substantial concrete buildings. We thus assume that the indoor shielding factor is represented by 0.8 (20% attenuation) [1]. As for the neutron component, the indoor shielding factor is assumed to be 1.0.

4.5 Expected dose rate for typical ALMA employee

To summarize the above considerations, the altitude dependence of the dose rate due to ionizing components near the ALMA site during the measurements can be fit by,

$$\dot{E}(z) \simeq (0.59 \pm 0.12) \times [0.21 \exp(-1.649z/\mathrm{km}) + 0.79 \exp(0.4528z/\mathrm{km})] \ \mathrm{mSv\,yr^{-1}}. \qquad (3)$$

This predicts the values at the AOS site (alt. = 5050 m) and the OSF site (alt. = 2800 m) to be $4.59 \pm 0.93\,\mathrm{mSv\,yr^{-1}}$ and $1.66 \pm 0.34\,\mathrm{mSv\,yr^{-1}}$, respectively. There is additional contribution due to neutron component, which is estimated to be $0.87\,\mathrm{mSv\,yr^{-1}}$ at the AOS site and $0.31\,\mathrm{mSv\,yr^{-1}}$ at the OSF site. Contribution of 25 air travels to Santiago is to be added. To obtain long-term average of these values, correction for the solar activity by a factor of 1.04 is needed. Subtracted probable contamination by terrestrial gamma rays in Chile at a level of $0.45\,\mathrm{mSv\,yr^{-1}}$ is finally to be added for total annual dose rate.

By assuming that an 8–6 turno employee works 8 hr a day at the AOS and sleeps at the OSF with indoor occupancy factor of 0.8 for gamma ray and 1.0 for neutron, and fly to Santiago to spend the rest of the weeks, and by adopting the indoor shielding factor of 0.8, the employee's exposure to cosmic rays is estimated to be $2.36\,\mathrm{mSv\,yr^{-1}}$.

Enhanced natural dose (the increment is $2.36 - 0.38 = 1.98\,\mathrm{mSv\,yr^{-1}}$) due to occupation can be understood as occupational dose. Provided that world average effective dose in the year 2000 was $2.4\,\mathrm{mSv\,yr^{-1}}$ (of which cosmic rays contributes $0.38\,\mathrm{mSv\,yr^{-1}}$) [1], the present results mean that the enhanced cosmic ray dose rate almost doubles ones annual dose. According to Table 1, this dose rate increment due to enhanced cosmic rays exceeds that of a typical worker engaged in nuclear fuel cycle while it is still lower than that of a typical aircrew.

5 Implication to site safety

5.1 Effects of low doses of radiation to human health

In general, radiation exposure can damage living cells, causing death in some of them and modifying others. Most organs and tissues of the body are not affected by the loss of even considerable numbers of cells. However, if the number lost is large enough, there will be observable harm to organs that may lead to death. Such harm occurs in individuals who are exposed to radiation in excess of a threshold level. Other radiation damage may also occur in cells that are not killed but modified. Such damage is usually repaired. If the repair is not perfect, the resulting modification will be transmitted to further cells and may eventually lead to cancer. If the cells modified are those transmitting hereditary information to the descendants of the exposed individual, hereditary disorders may arise.

Exposure to intense radiation has been associated with most forms of leukemia and with cancers of many organs, such as lung, breast and thyroid gland, but not with certain other organs, such as the prostate gland. However, a small addition of radiation exposure (e.g. about the global average level of natural radiation exposure) would produce an exceedingly small increase in the chances of developing an attributable cancer. Moreover, radiation-induced cancer may manifest itself decades after the exposure and does not differ from cancers that arise spontaneously or are attributable to other factors.

Radiation exposure also has the potential to cause hereditary effects in the offspring of persons exposed to radiation. Such effects were once thought to threaten the future of the human race by increasing the rate of natural mutation to an inappropriate degree. However, radiation induced hereditary effects have yet to be detected in human populations exposed to radiation, although they are known to occur in other species.

It has been discussed whether there might be a threshold level of exposure below which biological response does not occur or even radiation-associated initiating events in human tumors is expected. The latter effect called hormesis has been reported for rats exposed by 0.01–0.5 Gy radiation. However, extensive research seems neither supported nor disproved the linear relationship between the radiation dose and the risk for human populations, and UNSCEAR concluded that the linear relationship is valid as far as is known [1]. In any case, the risk due to enhanced cosmic ray dose seems extremely small[1] compared to the risks associated with low oxygen and enhanced UV intensity at high altitude sites.

5.2 Recommended action

The annual dose of an 8–6 turno employee who works 8 hr at the AOS and consequently stays about 1500 hr every year will be 2.36 mSv provided that the employee sleeps at the OSF and fly to Santiago twice a month. This value is comparable to the other occupational doses listed in Table 1. This sort of significant increase in dose rate associated with ones occupation is understood as occupational dose. In such cases the exposure of workers is restricted by internationally recognized limits: The International Commission on Radiological Protection (ICRP) recommended that the occupational exposure limit for workers should not exceed an effective dose rate of 20 mSv yr^{-1} averaged over 5 yr, with not more than 50 mSv in any single year [15]. The ICRP also recommended that the effective dose limit for female workers with reproductive capacity to be 5 mSv per 3 months, though this special limit is not necessarily applied to those who are not willing to bear a child and/or unable to be pregnant.

Considering that the expected annual effective dose at the site is far below the ICRP recommendation threshold for female workers with reproductive capacity, that the requirements in OSHA regulation 29 CFR 1910.1096 on occupational exposure to ionizing radiation or equivalents will not be violated, and that there is no risk of accidental exposure at critical level, there may be no need for the ALMA Safety Committee to make special considerations to this issue. However, considering that the amount and nature of exposure of the employees is similar to that of aircrews and that some of the employees are at the same time frequent flyers, it may be reasonable to follow regulations for aircrews [16], e.g.,

- The employees must be appropriately informed and educated regarding the potential risks of the occupational exposure.
- No controls are necessary for an individual whose annual dose can be shown to be less than 1 mSv.
- In cases that an effective dose greater than 1 mSv is expected, detail of the assessments of exposure must be recorded. If the assessed annual dose is less than 6 mSv, no further action needs to be taken.
- In case that annual maximum dose of an employee exceeds 6 mSv, individual monitoring must be carried out. Action is to be made toward reduction of exposure with the aim of preventing, where possible, annual doses in excess of 6 mSv. Records for individuals with annual exposure larger than 6 mSv must be kept for a minimum of 30 yr from the last annual exposure of more than 6 mSv or until the individual is 75 years of age, whichever is the longer period of time.

[1]International Commission on Radiological Protection (ICRP) estimates 12.5 ppm mSv^{-1} increase of expected risk of developing cancer [15]. In developed countries 21% of persons die form naturally occurring cancer.

Our understanding on the effects of low doses of radiation to human health is still very limited, and the regulation is to be updated in timely fashion.

6 Summary

Levels of radiation exposure in Chilean altiplano primarily due to cosmic rays were measured with pocket gamma ray dosimeters and a handy neutron rem counter. Comparison data were also taken at Antofagasta, Santiago, Mitaka, and on board the aircrafts to/from the site. Cosmic ray dose rate due to ionizing and neutron components were both shown to be several factors higher at the AOS than at the OSF: Measured gamma ray dose rates (including $\sim 0.45\,\mathrm{mSv\,yr^{-1}}$ contribution of terrestrial gamma ray) were $3.14\,\mathrm{mSv\,yr^{-1}}$ at Pampa La Bola (alt. = 4800 m) near the AOS site, $1.70\,\mathrm{mSv\,yr^{-1}}$ at San Pedro de Atacama (alt. = 2450 m) near the OSF site, $1.19\,\mathrm{mSv\,yr^{-1}}$ at Antofagasta (alt. = 30 m), $0.99\,\mathrm{mSv\,yr^{-1}}$ at Santiago (alt. = 520 m), $0.82\,\mathrm{mSv\,yr^{-1}}$ at Mitaka (alt. = 60 m), and 12–27 $\mathrm{mSv\,yr^{-1}}$ at altitudes of cruising aircrafts (alt. $\simeq$ 10000 m), respectively. As for the neutron component, altitude dependence is severer: Measured neutron dose rates were $0.80\,\mathrm{mSv\,yr^{-1}}$ at Pampa La Bola, $0.25\,\mathrm{mSv\,yr^{-1}}$ at San Pedro de Atacama, $0.02\,\mathrm{mSv\,yr^{-1}}$ at Antofagasta, $0.01\,\mathrm{mSv\,yr^{-1}}$ at Santiago, and 2.6–11 $\mathrm{mSv\,yr^{-1}}$ at altitudes of cruising aircrafts, respectively. These values at the ALMA sites are even higher than world average dose rates *at comparable altitudes*, probably reflecting enhancement of incoming primary cosmic rays near the South Atlantic Anomaly. After correction for the effects of solar activity and indoor shielding, we estimate that cosmic ray dose rate increment of an 8–6 turno employee working 8 hr at the AOS and sleeping at the OSF is a level of $2.0\,\mathrm{mSv\,yr^{-1}}$. As an occupational exposure, this dose rate increment due to enhanced cosmic rays exceeds that of a typical worker engaged in nuclear fuel.

At the ALMA site, cosmic ray dose rates are enhanced to the level that the effects on highly-integrated instruments such as correlators may not be negligible, and thus such effects are to be evaluated in quantitative manner.

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Table 1: World annual per caput effective doses in year 2000 [1]

Source	Average effective dose ($mSv\,yr^{-1}$)	Typical range ($mSv\,yr^{-1}$)
Natural background		
Cosmic rays	0.38	0.3 – 1.0
Terrestrial gamma rays	0.5	0.3 – 0.6
Inhalation (mainly ^{222}Rn)	1.2	0.2 – 10
Ingestion	0.3	0.2 – 0.8
Other general exposure		
Diagnostic medical examinations	0.4	0.04 – 1.0
Atmospheric nuclear testing	0.005	
Aftereffect of Chernobyl accident	0.002	
Occupational exposure		
Nuclear fuel cycle	1.8	
Industrial uses of radiation	0.5	
Defense activities	0.2	
Medical uses of radiation	0.3	
Aircrew	3.0	
Mining (other than coal)	2.7	
Mining (coal)	0.7	
Mineral processing	1.0	
Above ground workplaces (^{222}Rn)	4.8	

Table 2: Neutron (thermal–15 MeV) dose rate in ISS measured with BBND

UTC date (yy–mm–dd)	Altitude (km)	Longitude (deg)	Latitude (deg)	Dose rate (μSv hr^{-1})
ALMA site				
2001–04–04	379.86	292.25	−22.91	5.1272
2001–04–13	383.96	291.70	−23.27	5.4546
2001–05–17	390.28	292.16	−22.67	7.0472
2001–05–30	396.65	291.95	−22.92	6.5414
2001–06–18	395.02	291.73	−23.23	7.1542
2001–07–20	388.71	292.52	−22.87	6.4487
2001–07–29	399.11	292.10	−22.50	8.1894
2001–07–30	389.73	292.70	−23.12	7.4506
2001–09–01	397.41	291.99	−22.77	10.381
2001–09–13	397.68	292.29	−22.77	11.622
2001–10–10	389.63	292.24	−22.74	8.4045
2001–11–04	391.04	292.04	−22.76	7.6513
mean	391.59			7.6227
Mitaka				
2001–04–04	392.93	139.61	35.98	1.3481
2001–04–15	397.72	139.85	35.34	1.7913
2001–04–23	391.58	139.04	35.25	1.6698
2001–05–18	383.37	139.29	35.87	1.1245
2001–07–07	389.35	139.64	35.42	1.0392
2001–07–12	391.15	139.90	35.33	1.5134
2001–08–07	397.07	139.64	36.14	0.8815
mean	391.88			1.3383

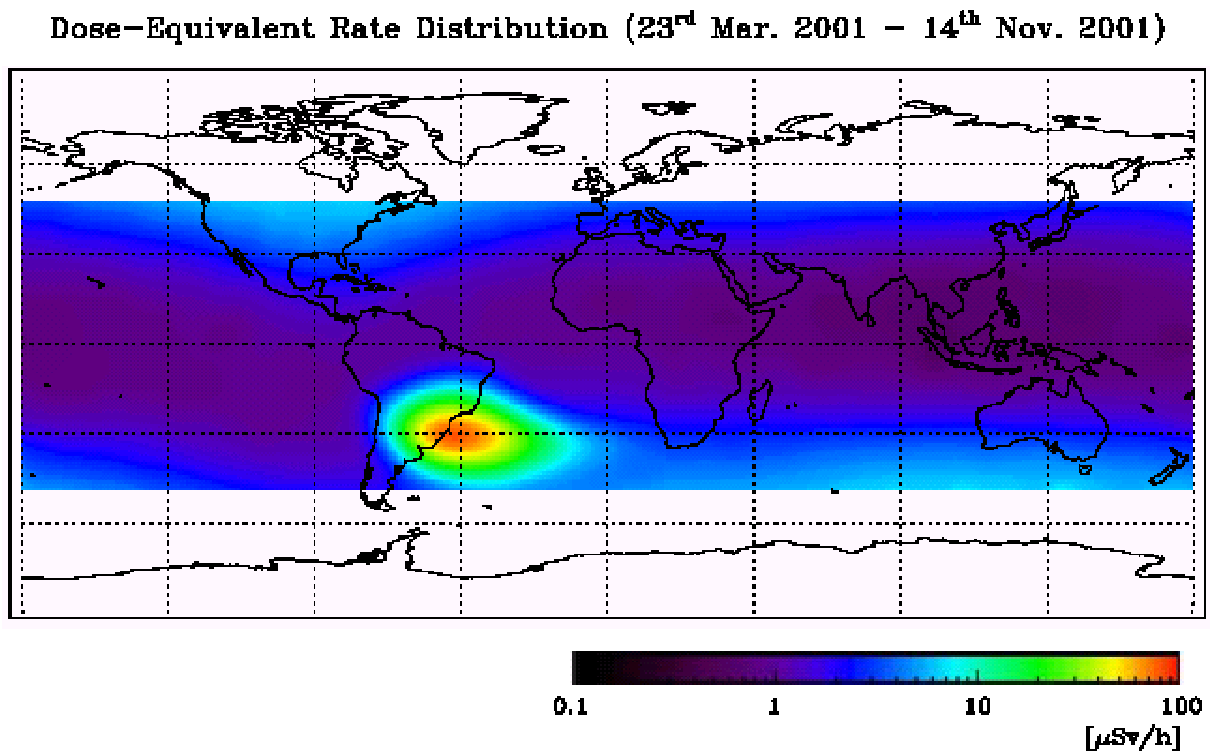

Figure 1: Spatial distribution of dose equivalent rate due to neutrons with energy range from thermal to 15 MeV, measured during 2001 March 23–November 14 with Bonner Ball Neutron Detector (BBND) aboard the International Space Station at an orbit about 400 km above the ground [7]. Note that the measured neutrons are not only primary but mostly secondary neutrons produced by interaction of primary ionizing cosmic rays with the walls of the ISS. The ALMA site is located at 23.0°S, 67.8°W.

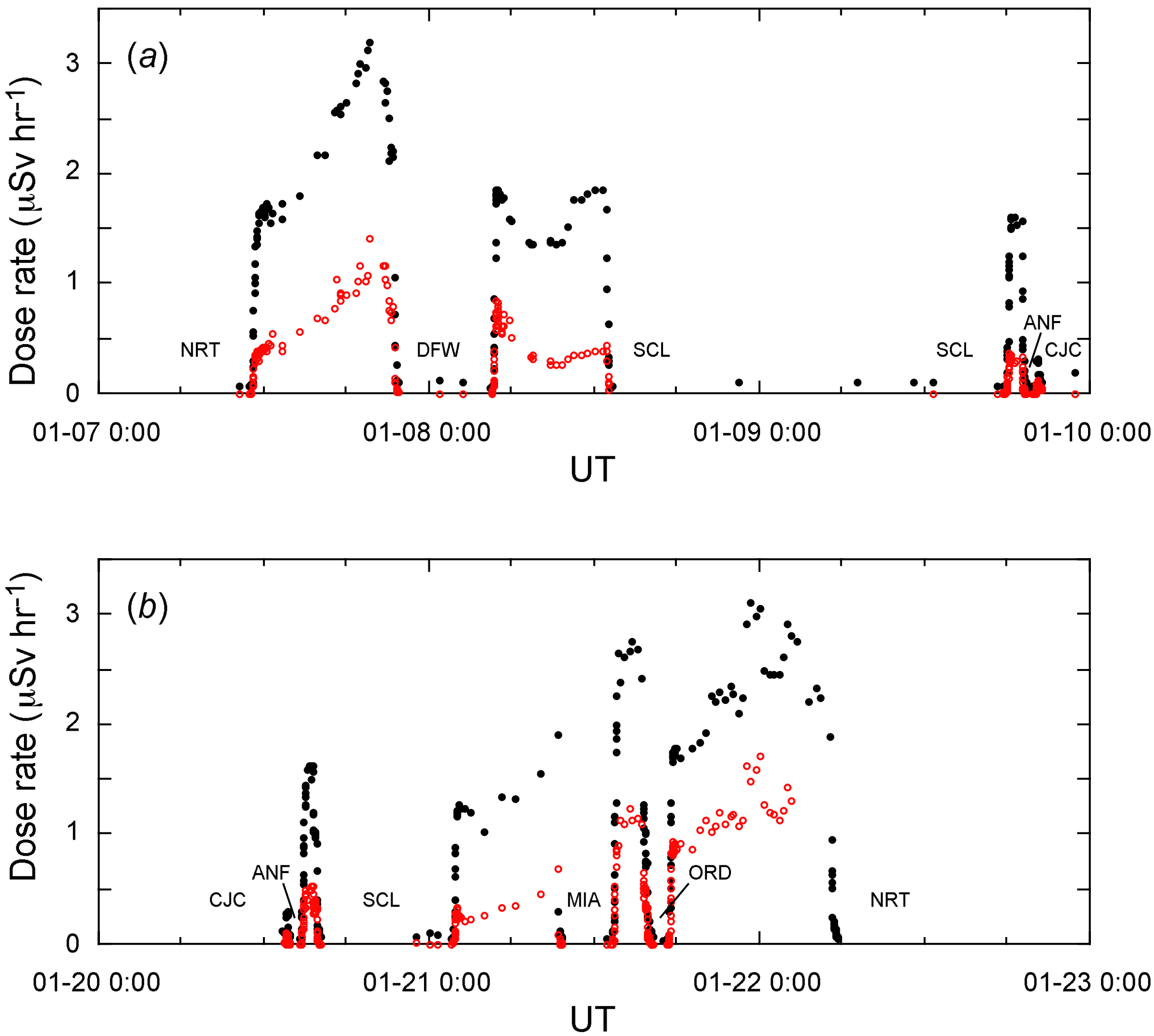

Figure 2: History of the measured dose rate during the travel from/to Narita to/from Calama. Both gamma ray (*black filled circles*) and neutron (*red open circles*) components are plotted. (*a*) Plot of the data taken from Narita to Dallas/Fort Worth (AA-060; 10.9 hr flight at cruising altitudes from 11278 m to 12496 m), from Dallas/Fort Worth to Santiago (AA-945; 8.8 hr flight at cruising altitude of 10668 m), and from Santiago to Calama via Antofagasta (LA-354; 1.6+0.4 hr flight). (*b*) Same as (a) but from Calama to Santiago via Antofagasta (LA-343; 0.4+1.4 hr flight), from Santiago to Miami (AA-912; 8.0 hr flight), and from Miami to Tokyo via Chicago (AA-153; 2.9+12.4 hr flight).

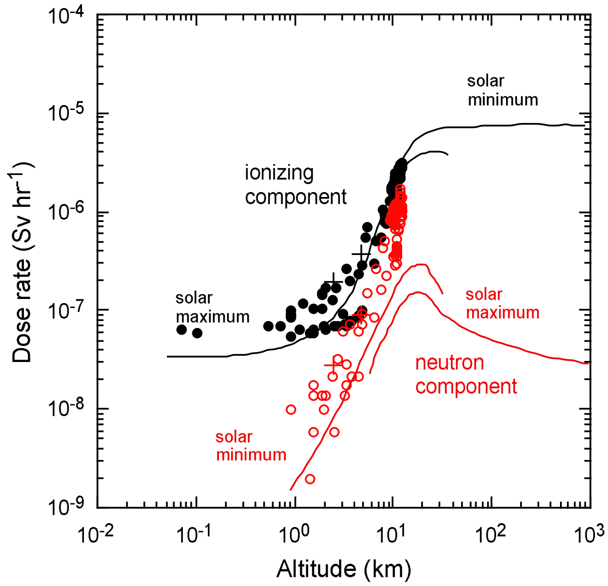

Figure 3: Radiation exposure due to gamma ray (*black symbols*) and neutron (*red symbols*) components measured at the ALMA sites (*crosses*) and on board the aircrafts (*open and filled circles*). Overlaid curves are the world mean altitude dependence of radiation exposure in Gy hr^{-1} [8]. Note that the effective dose rate of neutron component should be compared with curves corrected for radiation weighting factors in a range of 5–20. Also note that the present measurements were carried out when solar activity was maximum.

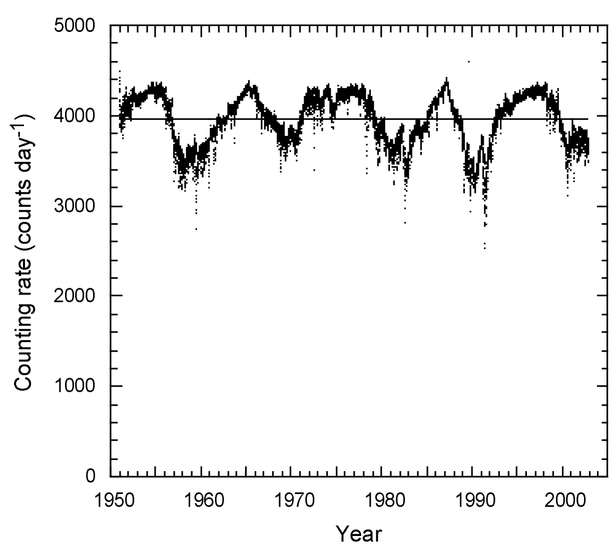

Figure 4: The cosmic ray intensity monitored by the Climax Neutron Monitor at Climax (alt. = 3400 m), Colorado, USA, from 1951 January 1 to the present [13]. Horizontal line corresponds to the mean value of 3957 counts day^{-1}. Average value during 2003 January was 3804 counts day^{-1}.