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Comment on galactic cosmic radiation dose to air crews

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Abstract. The possible effect of cosmic ray induce radiation dose on airplane crews is a subject of current study in a number of countries. The amount of radiation dose received by aircrews due to cosmic radiation is a function of (1) altitude above the surface of the earth, (2) the geomagnetic cutoff rigidity, and (3) the solar activity cycle. Of these three factors, the cosmic radiation change with altitude has the largest variability. This paper discusses the variables controlling the cosmic ray flux in the atmosphere and describes models and software that have been developed to provide quantitative information about the cosmic radiation exposure at flight altitudes.

1. Introduction

There is a public perception that any type of radiation is dangerous. Responses to questions about cosmic radiation exposure have many qualifications even though the radiation exposure from cosmic rays is small. The possible implications of sustained cosmic radiation exposure at aircraft altitudes on health are still being refined. The reason for these qualifiers is that radiation biology still has many outstanding questions to be resolved (Swenberg et al., 1993, Space Studies Board, 1996).

There has been some concern about the amount of radiation exposure to flight crews on commercial aircraft. Aircrew members represent a population that receives more radiation exposure than the general population living at sea level, and to the concern of many individuals, the long-term effect of this radiation exposure is not precisely known.

With the advent of long-range commercial aircraft and relatively inexpensive air travel, a large number of people travel via commercial aviation throughout the world. The fact that the "flying public" is exposed to a higher than average radiation dose is a cause of concern to some public advocacy groups. This concern is being addressed by a number of countries in a variety of ways.

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One example is the issuance of a US Federal Aviation Advisory suggesting aircrew member training on radiation exposure (FAA, 1994). In 1996, Japan's Radiation Council accepted the ICRP recommendations that the annual exposure level limit for aircrew members should be less than 20 mSv averaged over a five-year period (Fiorino, 1996). At the present time, to insure that the exposure to aircrew members is kept low, several European countries are legislating radiation limits and some are also limiting the number of flight hours allowed (European Commission, 1996; Lantos, 1999).

It has only been in the last few years that models that provide quantitative information on the radiation exposure, accurate to a few percent, have been developed. The technical reasons for this difficulty are detailed in the following sections.

2. The Natural Background Radiation Environment

In the United States, the average annual effective dose received by a member of the general public from all sources is ~3.0 mSv* (NCRP, 1993a). The majority of this exposure (~66%) is from naturally occurring radiation such as radon and other radionuclides. At sea level, only about 0.27 mSv of the annual dose is attributed to cosmic radiation.

It has been known, since the first cosmic radiation measurements, that the amount of radiation observed increases with altitude. For example, people living in Denver, Colorado, USA (altitude = 1600 meters) receive twice as much exposure to cosmic radiation as people leaving near sea level. In a country like the United States there is a large population living at both sea level and mountain altitudes. Medical records for these populations exist for a significant number of years thus making it possible to search for health problems that might be correlated to differences in the exposure to background cosmic radiation. When these

*A Sievert is the new SI unit of absorbed dose, which is one Joule of energy per kilogram of mass. A microsievert is one millionth of a Sievert, which is a very small radiation exposure. A millisievert is 0.001 Sievert. A Sievert is equivalent to 100 REM in cgs units.

studies are done, a surprising paradox is found. The population living at mountain altitudes is generally healthier and has a longer life span than the population living at sea level. The conclusion is that other factors must dominate, and exposure to the cosmic radiation at altitudes where people live does not appear to present a health hazard.

While the exposure at each location due to the natural radionuclides remains relatively constant, the amount of the cosmic radiation received is a function of (1) altitude above the surface of the earth, (2) the geomagnetic cutoff rigidity, and (3) the solar activity cycle. Of these three variables, the cosmic radiation variation with altitude is the largest. In the next sections we will briefly discuss each of these variables.

3. Cosmic Radiation at the Earth

Galactic cosmic radiation originates from outside the solar system with the intensity observed at the earth inversely proportional to the phase of the solar sunspot cycle. The propagation of cosmic radiation throughout the heliosphere is controlled by the turbulence of the solar plasma, and the turbulence within this plasma is a function of solar activity. The amount of galactic cosmic radiation present at any time in the solar cycle can be determined from the modulation parameter. Sometimes referred to as the heliocentric potential, this modulation parameter (φ) is an essential input to cosmic ray models. The current cosmic ray modulation theory is adequate to approximate the cosmic ray flux observed at the earth and on our most distant space probes. (See Belov, 2000, for a more detailed description of cosmic ray modulation.) Figure 1 illustrates the modulated cosmic ray intensity for almost five solar cycles as measured by the neutron monitor at Climax, Colorado, USA.

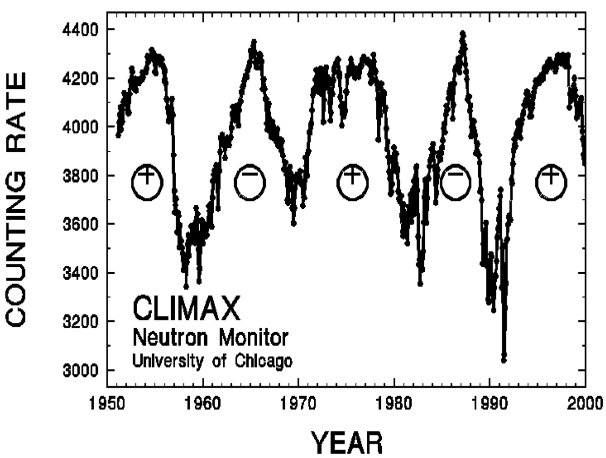

Fig. 1. The cosmic ray intensity as observed by the Climax, Colorado, USA neutron monitor. This is the longest continuous record of the cosmic ray intensity available, from 1951 to the present. Note the approximate 11-year solar cycle modulation. The + and – at the top of the circles indicate the polarity of the solar north polar magnetic field.

3.1 Atmospheric Shielding

The earth's atmosphere provides a shielding mass, at sea level, of about 1033 grams of matter per cm^2. Cosmic rays impacting the atmosphere generate nuclear cascades that propagate through the atmosphere. Higher energy protons (in the GeV energy range) will generate an atmospheric nuclear cascade, and these high-energy cascading particles have enough energy to continue the process to sea level. The minimum energy a proton must have to initiate a nuclear interaction sequence that may be detectable at sea level is approximately ~450 MeV.

4.2 Geomagnetic Shielding

The earth's magnetic field acts as a natural shield against the charged particles comprising the galactic and solar cosmic rays that impact the magnetosphere. In the equatorial regions of the earth only the most energetic cosmic rays above ~15 GeV can penetrate the geomagnetic field to the upper atmosphere. The amount of cosmic radiation that can penetrate the geomagnetic field gradually increases as the magnetic latitude changes from the equatorial to the polar regions until, in the region of the polar caps, galactic cosmic rays of all energies are present at the top of the atmosphere. The proton energy cutoff contours are illustrated in Figure 2.

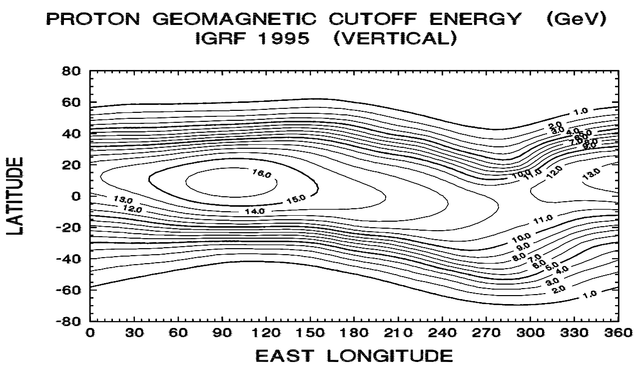

Fig. 2. "World map" of computed vertical cosmic ray cutoffs calculated using the IGRF 1995 magnetic field model 1995 (Sabaka et al., 1997). Note that the maximum cutoff energies are at the magnetic equator and the minimum cutoff energies are near the magnetic poles.

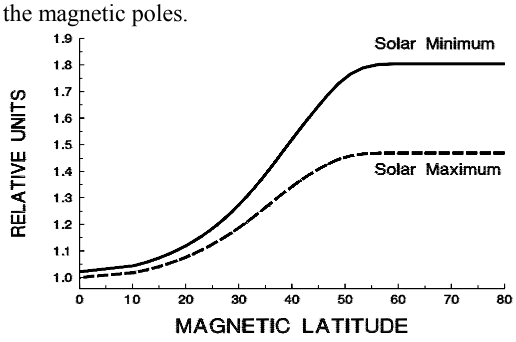

Fig. 3. Illustration of the cosmic latitude curve. The minimum value occurs at the equator and the maximum value at polar latitudes. The values are relative since the numbers vary with altitude and solar activity.

This variation in the cosmic ray cutoff results in a change in cosmic ray intensity as a function of latitude. There is a minimum in the intensity at the cosmic ray equator. The cosmic ray intensity increases with magnetic latitude until a maximum value is reached at upper mid latitudes (above ~50° geomagnetic latitude) where a constant intensity value is reached. The point where the intensity levels off is called the "knee" of the cosmic ray latitude curve (see Figure 3). The cosmic ray intensity in the polar regions (i.e. above the latitude knee) is constant because the shielding effect of the earth's atmosphere is larger than the cosmic ray cutoff. People living at high latitude, above the knee in the latitude curve, experience approximately twice as much radiation exposure due to cosmic radiation as people living in the equatorial regions at the same altitude.

4. Exposure to Cosmic Radiation at Aircraft Altitudes

At polar latitudes the sea level the dose rate is approximately 0.05 microsieverts per hour whereas at commercial aircraft altitudes (~35,000 ft) the dose rate can be the order of 4 microsieverts per hour (Reitz, 1993). This change with altitude is the largest of the naturally occurring variations, which are detailed in Table 1.

Table 1. Variation in Cosmic Ray Exposure.

Effect	Range of variation	
Altitude	Factor of 1000	Sea level to 80000 ft.
Latitude	Factor of ~2	Highest at polar latitudes.
Solar Cycle	Factor of ~2	Highest at high latitude.
Solar Protons	Variable	Highest at polar latitudes; Short lived events

The radiation exposure as a function of latitude has an approximate factor of two variation (the geomagnetic shielding effect illustrated in Figures 2 and 3) with a highest exposure rate in the polar regions. At high latitudes in the stratosphere there is another approximate factor of two variation over a solar cycle with more exposure during solar minimum than during solar maximum. These features are illustrated in Figure 4. This figure presents the computed radiation exposure rate due to cosmic radiation at various flight altitudes since 1955. Note that at the equator there is little variation in radiation dose as a function of the solar cycle; the small amount of variation in the equatorial region is most apparent at high altitudes. At high latitudes, the solar cycle modulation, although apparent, is relatively small at altitudes below 20,000 feet. The solar cycle modulation becomes significant at 40,000 feet and becomes very large above 55,000 feet. Use of specific information such as presented in this figure can remove much of the uncertainty in evaluating the radiation exposure during flights.

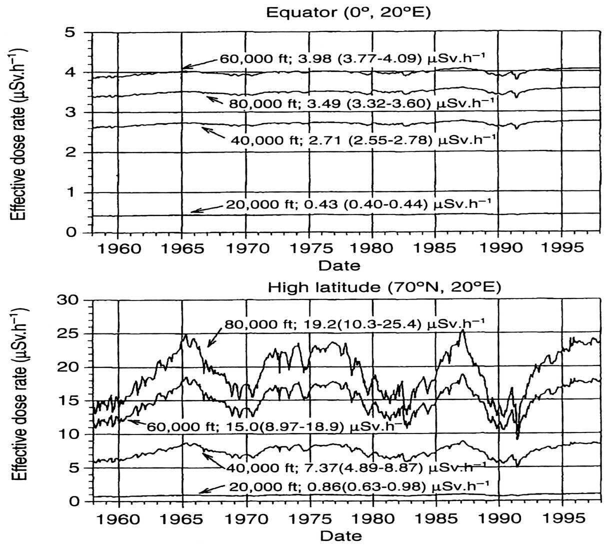

Fig. 4. Illustration of the radiation exposure at various flight altitudes since 1955 at equatorial latitudes (upper panel) and high latitudes (bottom panel). (Friedberg et al., 1999). Reproduced with author's permission.

4.1 Radiation Exposure Calculations

In previous years it has been difficult to obtain specific numerical radiation exposure values. To remedy this the US Federal Aviation Administration (FAA) has been developing a computer code to quantify the radiation exposure on any specific air route. The most recent version of this computer code, called CARI, can be obtained from: **http://www.cami.jccbi.gov/AAM-600/610/600radio.html** and is designed to operate on a personal computer. This computer program takes into account all of the factors previously discussed: the solar cycle variation, the geomagnetic cutoff effect, and atmospheric mass effect. The cosmic radiation modulation parameter for a specific flight date specifies the cosmic radiation flux at the earth's magnetospheric boundary. This galactic cosmic ray flux is then filtered through the geomagnetic field to determine the particle flux arriving at the top of the atmosphere at a specific location. This primary cosmic ray flux interacts with the atmosphere generating nuclear reactions that result in the secondary cosmic radiation. These secondary cosmic ray particles are then inventoried as a function of height in the atmosphere.

A significant part of the CARI software is based on the results of the LUIN computer code (O'Brien, 1978, 2001). This code transports the cosmic ray flux through the atmosphere, accounts for the nuclear interactions, and computes the flux and distribution of secondary cosmic ray particles as a result of these nuclear interactions. The computed particle fluxes in the atmosphere have been verified by comparison with experimental observations such as those tabulated by Allkofer and Grieder (1984). The radiation dose at any position and latitude in the earth's atmosphere is found by converting the particle inventory to dose in the manner specified by the International Commission on Radiological Protection (ICRP, 1991). The computed dose has been verified by comparison with dosimeters on a number of aircraft extending from commercial flight altitudes to high altitude U2 aircraft.

The CARI software can provide definitive answers to questions regarding radiation dose on aircraft flights. The current CARI software package contains a history of the cosmic ray modulation parameter as derived by O'Brien (O'Brien et al., 1991; O'Brien, 2001) from neutron monitor data from 1955 to the present.

Using the CARI software, the commercial aircraft flight radiation exposure can be quantified in a number of ways. The radiation exposure on any specific flight can be computed. If information for an individual aircrew member is desired, the monthly or yearly exposure on specific routes can be computed. In general, the highest doses per flight hour are received on air routes along the North Atlantic air corridor between the United States and Europe. Flights between the United States and Asia or Australia, between Europe and Africa, or between North and South America receive less radiation exposure per flight hour than flights across the North Atlantic.

The Concorde SST is a special case. Even though it flies at a higher altitude, the total flight time is shorter, and the total dose experienced by passengers on the Concorde is slightly lower than experienced by passengers on a commercial 747 over the same routing. This fact was specifically noted in a study of the radiation safety aspects of high altitude flight conducted by the US National Council on Radiation Protection and Measurements (NCRP, 1995). Table II gives examples of radiation dosage experienced on specific flight routes.

Table 2. Radiation Exposure due to Cosmic Radiation on Selected Flights.

Route (city to city)	Highest Altitude (Feet)	Flight Duration	Dose in mSv Solar Max	Dose in mSv Solar Min
Los Angeles - London	39000	11 Hr	0.055	0.065
Los Angeles - Tokyo	37000	12 Hr	0.031	0.040
New York - London	37000	7 Hr	0.023	0.040
New York - Lisbon	37000	7 Hr	0.020	0.031
New York - Athens	41000	10 Hr	0.042	0.067
New York - Paris	39000	7 Hr	0.036	0.057
New York - Paris (SST)	57000	3.5 Hr	0.031	0.052
San Francisco – Sydney	37000	14.5 Hr	0.040	0.050
New York – Hong Kong	37000	15.7 Hr	0.086	0.105
New York – Singapore	37000	18 Hr	0.098	0.111

It is also possible to compare radiation exposure on a specific flight with the natural radiation exposure at a specific location. For example, the exposure due to cosmic radiation on a flight from New York to London is approximately equivalent to the cosmic radiation exposure received in five weeks at Denver, Colorado, USA. An aircrew member consistently working on the New York to Athens route and logging 700 flight hours per year, would accumulate an annual exposure due to cosmic radiation of 4.2 mSv. This calculation assumes a solar cycle average exposure of 0.6 mSv per 100 flight hours. This accumulated dosage is considerably below the ICRP recommended limit of 20 mSv per year.

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