Bureau of Meteorology Space Weather Services

A Guide to Space Radiation

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1. History

It was at the end of the 19th century when people such as Becquerel discovered radioactivity, Roentgen discovered X-rays and Marie Curie was experimenting with electroscopes, that it came to be known that there existed an all pervasive external radiation source that was registered on instruments (primarily the discharge of electroscopes) when no known radiation source was present.

Some of this external radiation could be attributed to radioactivity in the rocks composing the Earth, but in 1912, an Austrian, Victor Hess, in an historic balloon ascent showed that part of the radiation came from above. As he lifted off the ground the radiation at first decreased (as the distance from terrestrial rocks increased), but then it rapidly increased to several time the level observed on the ground.

This new radiation was called cosmic radiation and was the subject of intense study by physicists for the next half century. It was initially thought to be very high energy gamma radiation, but was later shown to be extremely penetrating particulate radiation.

One of the driving forces for a world-wide space weather observing network came during the Apollo era when NASA set up the Solar Particle Alert Network (SPAN) to watch for solar events that could produce radiation dangerous to the Apollo astronauts. The Bureau of Meteorology Space Weather Services (SWS) personnel manned the SPAN site at Carnarvon. The SEON network is a direct outgrowth of SPAN (and of course SWS jointly manages one of the SEON sites at Learmonth), and the SWS Culgoora Observatory was initially the SPAN site and equipment transported to its present location. The radio side of Carnarvon SPAN initially went to the Fleurs Observatory (University of Sydney) near Kemp's Creek, but is now also located at Culgoora. SWS space weather monitoring thus owes a lot to space radiation.

2. Radiation Types and Units

Radiation is a term that can be used to refer to anything that radiates. In physical terms it covers both electromagnetic radiation (from radio waves to gamma rays) and sub-atomic particle emissions. These particles may include electrons, protons, neutrons, helium nuclei, and a host of sub-nuclear particles such as mesons (muons and pions), neutrinos and many others.

In popular language, the term radiation is commonly used to refer to ionising radiation; that is, radiation that has sufficient energy to remove electrons from or ionise atoms in the materials it interacts with. Now the energy required to remove an electron from a typical atom is usually in the order of a few electron volts (where 1 eV has an energy of about 10^{-19} Joule), so any radiation that has particles (or photons) with an individual energy above this amount can be regarded as ionising. For electromagnetic energy, this corresponds to ultraviolet, X and gamma radiation (in order of increasing energy).

Radiation with energies of only a few tens of electron volts are absorbed very easily by very thin layers of matter (a piece of paper is sufficient to seriously attenuate UV energy). Except for superficial reactions on naked skin, most radiations need an energy of least a few tens of keV before they become biologically significant. Neutrons are an exception to this rule because they are uncharged particles. These particles can thus "sneak" past the electromagnetic potential barrier of the nucleus and have the capability of inducing radioactivity in the materials they invade.

When naturally occurring radioactive materials were first investigated it was found that they emitted three different types of radiation. These were termed alpha, beta and gamma. We now know these to be:

- alpha -helium nuclei (particulate radiation)
- beta -electrons (particulate radiation)
- gamma -photons (electromagnetic radiation)

There are a number of units that are required to describe various types of radiation and its effects. To complicate the matter still further, there was change of units in January 1978 to conform with SI (Systeme Internationale) principles. The old set of units still regularly appears in publications, alongside the new.

The unit usually used to describe the energy of the radiation is the electron volt and its multiples (eV, keV, MeV, GeV, TeV). One electron volt is the energy possessed by an electron after it has been accelerated through a potential difference of one volt. It is a very small unit in terms of our everyday experience (1eV = 1.6×10^{-19} J), but then so is an elementary particle. It has not been replaced by an SI unit in general use simply because SI units, even with appropriate very small prefixes are too large. There is an approved SI prefix that could be used (attoJoule = 10^{-18} J), but so far it has not been.

For radioactive materials a unit of activity describes the number of disintegrations per second. In the old system the unit was the Curie and this was the number of disintegrations per second that occurs in precisely on gram of pure radium.

1 Curie (Ci) = 3.7×10^{10} disintegrations per second
The new unit of activity is the Becquerel where:
1 Becquerel (Bq) = 1 disintegration per second
Thus 1 Bq = 27.03 pCi (picoCuries)

The remaining units we need to consider refer to the effects of radiation on matter. The first of these units used was the Roentgen (R) and this was referred to as the radiation "exposure dose". It was an amount of X-radiation that produced a certain amount of free charge (of both signs, positive and negative) in a cubic centimetre of dry air at 20 degrees Celsius. This unit is rather specific to the type of radiation and to the material (dry air) being considered. The same radiation may produce an entirely different amount of ionisation in a different material. For this reason the Roentgen is no longer used. It was replaced by a quantity known as the "absorbed dose".

The "rad", short for radiation, was the old unit of radiation absorbed dose. It is that amount of any radiation that deposits 10 milliJoule of energy in a kilogram of material. The numerical value was chosen so that in dry air, one rad is approximately equal to one Roentgen. The new SI unit of absorbed dose is the Gray where:

1 Gray (Gy) = 100 rad = 1 J / kg

When dealing with biological effects, it is necessary to introduce yet another unit, and this is because equal radiation absorbed doses from different types of radiation have differing biological effects. A dose of alpha radiation is much more damaging to biological tissue than the same dose from gamma radiation. The old unit for biological dose was the rem (rad equivalent mammal/man). The relationship between the rad and the rem was given by the formula:

rem = rbe * rad

where the rbe was the relative biological effectiveness of the specific radiation in question. Some values of rbe are as follows:

X-rays	rbe = 1
gamma rays	1
neutrons	10
alpha particles	20

The new SI unit for biological dose is the Sievert (Sv) where this is defined in terms of the Gray as:

Sievert = QF * Gray

Note that the term QF or quality factor has replaced the rbe. QF considers not only the type of radiation but also its energy, which can alter the biological effect. Thus, the relationship between the old and new biological units is:

1 Sievert (Sv) ≈ 100 rem
1 mSv ≈ 100 mrem (milli or 1/1000)
1 µSv ≈ 100 µrem (micro or one millionth)

The use of the approximate equality sign in the above relations is to indicate that QF and RBE are not exactly the same. Note that all quantities and multiples in the above table are used in the current literature and it is necessary to be able to convert from one to the other.

Radiation units are not much use until one develops a feel for the magnitudes of different radiation fields. These are described in the following three sections.

3. Physical Effects

The effects of ionising radiation can be many and varied, welcome and unwelcome, but they basically all rely on the ionisation of the materials they interact with.

The ionosphere is a good example of a (generally) welcome effect of ionising radiation (ultraviolet and X-radiation).

An unwelcome example is the impact of high energy solar protons on satellite solar cells to reduce their life. This is an example of a bulk effect whereby the photovoltaic effect of silicon is reduced through the creation of undesired intermediate energy levels or traps in the semiconducting material. This decreases the mobility of the charge carriers and thus reduces the amount of current that the cell can provide.

There are also events related to the interaction of a single cosmic ray particle with a small region of sensitive matter, such as the memory cell in a high density integrated circuit. Such an interaction is generally known as a single event upset (SEU) in which the memory cell is temporarily changed to the opposite state (i.e. a zero becomes a one or vice versa).

The following table gives some examples of the various radiation dose sensitivities at which different materials suffer effects (the lower number is the dose for the start of an effect, the higher number the dose at which the effect saturates (i.e. no further effect/damage)):

Photographic materials 0.1 to 50 rad = 1 mGy to 500 mGy
(some specialised photographic emulsions are considerably more sensitive than this, and in fact can record the track of single radiation particles)

Germanium Radiation Detectors 10 to 500 rad = 0.1 to 5 Gy

NMOS Microprocessors 500 to 5000 rad = 5 to 50 Gy

MOS Transistors (SiO_2 insulator) 10,000 - 200,000 rad = 100 - 2000 Gy

Optical Glasses 200 - 7000 Gy

The glass becomes coloured/stained by the radiation dose.

Semiconductor Diodes 1000 - 100,000 Gy
(this refers to interactions produced by charged particles. Neutrons produce effects at much lower dose rates. And in fact normal 1N4148 or 1N4004 diodes - which are widely used in radios and TV, etc. - show a response to fast neutrons over the range 10 to 100 rad [0.1 to 1 Gy] where in the forward voltage drop of the diode increases from the normal 0.6 volts to around 5 volts at the highest dose.

Thermal Coatings 30,000 - 3,000,000 Gy

Plastic Insulators 30,000 - 10,000,000 Gy

The actual effect on the abovementioned items varies according to the material. At very high doses, metals become very brittle and lose their strength.

4. Biological Effects

Biological effects take place at much lower doses than for effects on inorganic materials. Effects are generally divided in two classes, carcinogenesis and teratogenesis.

Knowledge that X-rays could produce adverse effects in biological systems first became known around 1900. However, it was not realised that radioactive materials could produce similar (cancerous) effects until almost the 1950’s.

In 1927 Muller demonstrated that the exposure of germ cells (sperm and/or ova) to X-rays resulted in changes in the hereditary material. This finding was confined to biological circles until the use of atomic energy for military purposes burgeoned in WWII.

Biological effects, like physical effects, are a result of ionisation of biological material (protoplasm) by the ionising radiation. This creates ionised molecules or free radicals in the cells.

The free radicals are generally ionised oxygen or hydrogen atoms (most of biological tissue is water), and these can lead to the formation of powerful oxidisers such as hydrogen peroxide. The subsequent redox (reduction/oxidation) reactions that occur can change the cell chemicals that are necessary for normal function. If the intensity of the radiation is sufficient and large numbers of free radicals are created in a single cell, then the cell may well become incapacitated and die. If that cell happens to be a single-celled organism, then the organism will die. In plants and animals, the cell will usually be part of a particular organ in the creature. As an organ is generally made up of a very large number of cells, the death of a single cell is of no consequence. However, if a substantial fraction of the cells comprising the organ are killed, the organ will die, and if the organ is critical to the organism then it too will die.

Biological organisms have a wide range of individuality and thus of tolerance to radiation levels. The quantity that is normally used to describe the lethality of radiation to an organism is termed the LD-50/30. This means a lethal dose for 50% of the population to die within 30 days. Various authors quote an LD-50/30 for humans of between 300 to 700 rem (3 to 7 Sv) with the most popular value being around 400. It is not easy to be precise in this regard. Most people don't volunteer for these experiments, and it is necessary to use populations who have been unknowingly or unwillingly exposed to these levels. In these circumstances estimation of actual doses is not easy.

Another effect can occur if the radiation creates damage not in the cytoplasm, but in the nucleus of the cell. Damage can occur in the DNA that gives instructions for the cell's metabolism. This can then be interpreted by the cell in a number of ways. A particularly nasty way of interpretation is when the instructions call for a different type of cell to be formed creating a new amorphous organ through rapid and uncontrolled cell division. This is the process of carcinogenesis. Now the cell DNA is fairly resistant to damage as long as the dose rate is not too high. This is because DNA comes as two redundant intertwined strand, and if one of the strands is damaged, it can usually be repaired by comparison with the undamaged strand. However, occasionally this process does not work and cancer results. Such a change in the DNA of a body cell is called a somatic mutation.

If the DNA damage occurs in a germ cell (i.e. a sperm or an ovum), and if (a very unlikely possibility, particularly in the case of a spermatozoon) that germ cell just happens to be used in the formation of a new individual, then a hereditary change is produced in the new life. In general genetic mutations are fatal, and the new life will rarely make it past the embryo stage, and the female may never be aware of what happened. If the new organism develops in the womb and is born, the mutation may or may not be expressed (it may be recessive or it may be dominant). It may also be beneficial, neutral or deleterious.

The evidence for genetic mutation induction by radiation is very limited and very ambiguous. The incidence of cancer is now assigned a definite quantitative linear relationship to radiation dose, but even that is often called into question, and is acknowledged to be made on the basis of (very conservative) assumptions that are not always compatible with experimental results.

The sources of data for biological analysis of radiation effects come from:

- Early radiation (X-ray) workers / radiologists
- Radium painters (mostly teenage girls in the 1920's)
- Japanese atomic bomb survivors
- People exposed to fallout from H-bomb test at Bikini atoll
- Medical patients receiving radiation treatment
- Uranium miners
- People exposed to nuclear reactor accidents like that at Chernobyl and Fukushima

Although the dose-cancer relationship is believed by a majority to be on solid ground, the same cannot be said of radiation teratogenesis. In particular, the results on this from the Japanese atomic bomb surviving females who had a fetus irradiated in utero seem to contradict the results of much lower exposures. The following table tells the story:

Surveys of births in Hiroshima/Nagasaki versus Controls

Group	Dose (rad)	Births	Stillbirths	Congenital Abnormalities
Hiroshima/ Nagasaki	8 - 200	33,181	1.65 %	0.89 %
Non irradiated controls	-	31,559	1.29 %	0.92 %

Neither the difference in the stillbirth rate or congenital abnormality rate between the two groups is statistically significant.

There is a generally agreed perception that the unborn foetus is more sensitive to in-utero radiation than it is in later life. (This is consistent with the finding that in general, rapidly dividing cells show more radiation sensitivity than do cells in mature organisms). In particular the sensitivity appears to be particularly acute to the developing Central Nervous System (CNS) from 8 to 25 weeks gestation age. It would thus appear to be particularly desirable to keep in utero exposure to an absolute minimum during this time. This finding is based on observations of one group alone (again the Hiroshima/Nagasaki survivors). The ICRP even has calculated a figure of -30 IQ/Sv. That is, a mental retardation of 30 IQ points results from an absorbed dose of 1 Sievert. Considering the controversy surrounding the interpretation of IQ tests, this is indeed a bold claim, but does indicate the mental retardation that can occur with in utero exposure during this time period. Outside this time frame, this significant radio-sensitivity appears to be lost. It is a particularly useful time frame, because it allows two months for the detection/realisation of the pregnancy before action must be taken (such as to remove a pregnant air crew member from flight duties).

5. Radiation Levels and ICRP Safety Recommendations

Typical radiation levels are:

Background radiation dose 100 millirem = 1 mSv per year
(This is the dose in a temperate region of the Earth away from radioactive rock and living in a timber house. It may increase significantly in certain areas of the world and in block/brick houses. In southern France it is typically 300 millirem = 3 mSv and on the south-western coast of India it reaches 1.5 rad = 15 mSv due to the presence of monazite sands which have a high percentage of thorium. In some parts of the USA in houses with little ventilation it can also reach 10 mSv or higher due to the accumulation of Radon gas).

Lowest radiation dose that can be clinically detected 20 rem = 200 mSv
(the first body system affected in man is the autoimmune system - the white blood cell count is decreased)

Single whole body dose required to produce radiation sickness 100-200 rem = 1-2 Sv

Medical X-ray procedures 5-100 millirem = 50 µSv - 1 mSv

Mean Lethal whole-body dose for man 400 rem = 4 Sv = 4000 mSv

Single localised (gonadal) dose to produce sterility 500 rem = 5 Sv

Localised fractionated doses used in radiotherapy 500-5000 rem = 5-50 Sv

The natural annual background radiation comes from a variety of sources. A typical breakdown might go as follows:

Cosmic radiation 28 millirem = 0.28 mSv
Terrestrial radiation 51 millirem = 0.51 mSv
Internal body radiation 21 millirem = 0.21 mSv

The internal body radiation comes mostly from the potassium-40 in the body (say 19 millirem = 0.19 mSv) with 2 millirem (= 0.02 mSv) from other radioactive elements such as carbon-14.

Note that all of the above figures can vary widely according to location on the Earth and lifestyle.

As an example consider the mean annual outdoor doses for two locations:
Dunedin, New Zealand 37 millirem = 0.37 mSv
Rome, Italy 181 millirem = 1.81 mSv

In 1928 the International Society of Radiology (ISR) sponsored formation of the International Commission of Radiological Protection (ICRP), an independent organisation which makes recommendations in the field of radiological protection. Over the decades since its inception the ICRP has continued to reduce the safe limits of radiation exposure for both occupational workers and the general population. Many times these reductions have not been based on unequivocal evidence of deleterious radiation effects, but on assumptions that are conservative extrapolations from higher radiation doses and dose rates. They are mostly driven by the ALARA principle (As Low As Reasonably Achievable). A large number of authorities in the field of radiation biology consider the current standards quite conservative.

The current ICRP standards were defined in the document ICRP-103 which was issued in 2007. The suggested limits are divided into two classes: one for workers exposed to radiation in the course of their duties, and one for the general public. One reason for the division is a consideration of the "genetic load" that the human population should bear. It is considered that a select portion of the population can withstand a higher dose than the general population and still maintain this total genetic load within acceptable limits. The dose limits are:

Occupational dose limit: 20 mSv per year averaged over a defined period of 5 years with no more than 50 mSv in a single year.

General public dose limit: 1 mSv per year averaged over 5 years.

The ICRP notes that "the above dose limits do not apply to medical exposures, to natural sources of radiation and under conditions resulting from accidents". In other words, these are limits above and beyond "normal" background exposure.

The above figures are a very limited extract of the ICRP recommendations but should suffice here. It should be noted that this latest issue of ICRP recommendations is considerably stricter than what existed before the earlier ICRP-60 document published in 1990. They are of concern to workers in not just the nuclear industry. Coal miners in some areas have had difficulty in keeping below these limits (coal often contains radium and other radioactive elements). They are certainly good limits to work to, but given the wide variation in natural background radiation (of at least 1 mSv/year), maybe we shouldn't be too concerned if we exceed them (as does the frequent visitor to Antarctica).

6. Radiation and the Space Environment

Space radiation has three basic sources:

- Galactic Cosmic Radiation (GCR)

- Solar Radiation, consisting of both low energy radiation and the high energy component normally referred to as solar cosmic radiation (SCR)
- Planetary Trapped Radiation

We now know that the primary GCR (as observed in space) consists mostly of protons with energies extending all the way up to about 10^{22} electron volts (an energy much higher than can be achieved by any Earth based atomic accelerator - which is usually measured in GeV or Tev [10^{12} eV] at the most). Mixed in with the protons are a small amount of heavier nuclei, predominantly helium, but extending all the way up to iron. It is thought that GCR is probably generated in supernova events, and then accelerated by galactic magnetic fields to the energies we observe.

Although the Sun emits both electromagnetic and particulate radiation over a very wide energy range, the term SCR is usually reserved for the highest energy solar radiations that are emitted during very energetic solar particle events (SPE's). The energies of protons emitted during these events is typically on the order of several tens to hundreds of MeV. Some very rare events can reach a few GeV (and these are significant to aviation).

The abundance of GCR decreases as a function of energy. That is, there are a lot of low energy cosmic rays, and fewer as we consider higher energies.

For low Earth orbits, which are where most of the manned missions to date have occurred, the major source of radiation comes from the Van Allen (trapped) radiation belts. Below about 1500 km the doses from this source are tolerable, and result mostly from passage through the infamous South Atlantic Anomaly (SAA). This is a region where the trapped radiation comes closest to the Earth because of the peculiar tilt and offset of the magnetic axis from the geographic axis. Most of this radiation is low energy and easily shielded. However, the occasional higher energy particles can cause an interesting biological effect. It was first noticed by Gemini astronauts that when passing a particular point in the orbit (later identified as the SAA) they could see flashes of light, even when they had their eyes closed. This was eventually explained as the radiation particles dumping enough energy in some of the retinal cells to activate a neural response that was interpreted by the brain as a flash of light. (This is not the first instance of this phenomenon. Rutherford was said to hold parties in the early part of the 20th century in which he would ask his guests to close their eyes. He would then hold a small vial containing a radium salt in solution close to their face, and they could "see" the vial through their closed eyelids!) We probably all experience this phenomenon from time to time with ground level GCR, but its infrequency amongst our daily activity makes us unaware of its significance.

When we get into the heart of the Van Allen radiation belts, the radiation dose rate becomes very large, in fact large enough to start affecting electronic components after many orbits, if design considerations have not used radiation hardened components (such as Gallium-Arsenide IC's instead of Silicon ones). The GPS satellites live in these conditions and are designed with radiation hardening. Astronauts must pass quickly through the trapped radiation belts on their way to the Moon or to Mars.

In low Earth orbit, the geomagnetic field provides substantial shielding against both low energy GCR and most SCR. On long duration interplanetary voyages astronauts will experience normal GCR radiation doses that are way outside the ICRP guidelines, and possibly SCR during times of high energy particle events that are fatal.

The table below indicates some radiation doses that might be experienced in various space situations at 1 AU, outside Earth's magnetic field, except for the Van Allen belt radiation entry.

Source	Component	Unshielded	Spacesuit	Spacecraft
GCR	positive ions	0.002 rem/hr	0.002 rem/hr	0.002 rem/hr
Solar wind	positive ions	10^{-5} rem/hr	0	0
Medium flare	positive ions	100 rem	50 rem	0.3 rem
Max flare	positive ions	10^5 rem	5×10^4 rem	350 rem
Van Allen	positive ions electrons	60 rem/hr 10^5 rem/hr	30 rem/hr 10 rem/hr	0.3 rem/hr 1 rem/hr

It is interesting to compute from the above table that the yearly dose from GCR for an astronaut undertaking a long voyage, say to Mars, comes to about 20 rem (200 mSv),which is 10 times the ICRP recommended occupational limit.

The suggested exposure limits for Apollo astronauts are also interesting when compared with today's ICRP recommendations. Values are in rem.

Constraint	Bone marrow	Skin	Ocular lens	Testes
Av. daily rate	0.2	0.6	0.3	0.1
30 day dose	25	75	37	13
Yearly	75	225	112	38
Career	400	1200	600	200

Note that solar radiation only becomes a significant hazard for orbital inclinations greater than about 50 degrees and at altitudes above a few Earth radii. It is very unlikely that the dosimeters carried by space shuttles will ever trigger an emergency response action plan. It is believed that the only time any significant radiation has been measured was during the GLE of October 1990, and that even then the level was well below response threshold.

A new type of solar space radiation has now been confirmed on at least three instances over the last two decades, and that is solar neutrons. This implies that in a very few flares, the temperatures reached are on the order of 12-15 million Kelvin. This is high enough to initiate fusion on the surface of the Sun! Previously it had been thought that only the solar core could sustain a fusion reaction. The neutrons detected at Earth were fusion neutrons, left over from the combination of two or more nuclei.

Space radiation studies have gained more prominence with the International Space Station in orbit, possible future missions to the Moon and Mars, and with an increasing concern displayed by some authorities to aviation radiation hazards, as we shall discuss in the following section.

7. Radiation and Aviation

The issue of aircrew exposure to cosmic radiation whilst in flight has gained increasing attention in the last decade.

The FAA issues an updated advisory circular (120-61 In-flight Radiation Exposure) which provides information and links to sources of detailed information for air carriers to use in informing crewmembers about in-flight radiation exposure.

The FAA Civil AeroMedical Institute (CAMI) has been involved in the continuous development of a computer program (CARI, the latest version as of July 2004 is CARI-6) which computes integrated galactic cosmic radiation dose over the course of a specified flight).

In May 2000, the European Union finally agreed to legislation regarding in-flight radiation. The requirements appear to be three-fold:

- All European airlines to provide mandatory training on in-flight radiation to all aircrew.
- All aircrew on European airline flights are to be individually assessed for total radiation dose. Such assessment can be carried out by computer modelling, and does not require the carrying of personal dosimeters during flights.
- All declared pregnant airline aircrew are to be removed to ground duty for the duration of the pregnancy and whilst breastfeeding.

Essentially, GCR in the atmosphere is a function of three variables, geomagnetic latitude, altitude (strictly pressure altitude), and solar activity. The general effect of solar radiation is to reduce the level of GCR. This it does through the shielding action of interplanetary magnetic fields that are carried away from the Sun in the solar wind.

Only very, very rarely does a solar flare accelerate particles to energies above one or more GeV that can penetrate the Earth's magnetic field defences and cause a significant increase in the overall radiation environment to terrestrial aviation. In fact, it is often cited that only eight such events have occurred since 1955 (the "Carrington Event" in September 1859 is the largest in the last 500 years). These eight "super" solar particle events are listed below:

23 February 1956
17 July 1959
13 November 1960
09 August 1972
20 October 1989
24 March 1991
15 July 2000
28 October 2003

It is interesting to note that these outstanding solar particle events (producing what is called a ground level event or GLE), are in general not related to the overall solar activity. They are produced by particular solar active regions that may occur at any time in the solar cycle. It is useful to realise that the event of 1972 occurred in cycle number 20 which had one of the lowest maximum sunspot numbers of any of the cycles since 1955.

The prediction of SPE's is quite uncertain, although Pat McIntosh was successful at the Leura Solar Terrestrial Predictions conference in 1989. His pronouncement of an imminent proton event at the beginning of the conference was rewarded by an eruption leading to relativistic proton emission only a few days later. In this instance, the sunspot group in question had its neutral line rotated by 90 degrees to align in the north-south direction. Despite this success, it must be admitted that this type of prediction is rarely successful, and thus this type of very rare event presents a small but incalculable hazard to aviation operations, when it may result in an increase in the overall cosmic radiation level in excess of 1500% (this increase was measured at the Ottawa neutron monitor station for the February 1956 event).

Some simple approximations can be given for the variation of GCR with the three parameters mentioned above. The variation with geomagnetic latitude (somewhat different from geographic latitude) is such that the intensity doubles in moving from the equator to the poles. The increase is not linear, and in fact saturates at about 60 degrees latitude. Thus it rises from the equator, more slowly at first and then more quickly until it turns over to plateau around 60 degrees north or south.

The variation with altitude is such that, very approximately, the intensity doubles for every 2000 metres (2 km) increase in height above the surface. This continues up until an altitude of about 20 km whereupon the curve turns over and starts to fall. At 20 km the GCR intensity is very roughly

50 times the ground level intensity. After this it falls back down and then plateaus at a level of 25 times ground radiation intensity by the time an altitude of 40 km is reached. This unusual behaviour is explained by the interaction of the primary GCR (mainly protons) with the Earth's atmosphere. Above 40-50 km one is experiencing direct primary radiation. Below this level the atmosphere starts to become thick enough that the primary radiation starts to collide with atmospheric molecules and produce secondary radiation. The intensity of the secondary radiation increases down to an altitude of 20 km below which the atmosphere becomes so thick that secondary radiations start to be absorbed. What this means is that a high altitude reconnaissance pilot will experience a greater radiation dose rate than an astronaut flying a space shuttle. Of course the astronaut is flying for a lengthier period of time and thus their total dose will be larger.

The variation of GCR with solar activity is not a simple function of any widely available solar variable such as sunspot number or solar radio 10 cm flux. Although it shows a high correlation with these, it also shows substantial variations at a given level of SSN or F10.7. However, if these must be used as surrogate indicators, we in general note that the GCR decreases as the SSN increases. The decrease is usually no more than about 30% by the time we reach an SSN of about 150 after which it levels off (i.e. shows no further decrease). Whether this plateau effect is real or is due to limited data is questionable. It should be noted however that several other phenomena, including ionospheric critical frequencies show a similar plateau effect above a SSN of 150.

The deepest decreases in GCR occurred in solar cycle 22, due to a number of particularly high density coronal mass ejections just after the peak of the cycle (1990-91). This decrease was not only noted at the Earth but was evidently in effect throughout most of the solar system (as James Van Allen noted in a JGR paper on measurements from the Voyager probes which were then a substantial fraction of the way to the heliopause, the boundary where the solar wind meets the intragalactic stellar wind).

The CARI-6 aviation radiation dose program is freely available from the CAMI FAA web site (see references), and may be used to calculate point dose rates at any selected geographical coordinates, altitude and date (the last variable giving the solar activity shielding factor). It may also be used to compute total aircrew radiation doses for a specified flight at specified altitudes and dates. The model is fed by actual ground level GCR rates from two cosmic ray neutron monitors, one in Canada and one in the polar region. The aforementioned web site provides this data in the form of a heliocentric potential (the HCP) each month so that the model can be updated. The HCP is not provided in real time, but the following month. The CARI-6 program was developed by staff at CAMI (FAA) with the help of outside scientists including Smart and Shea from AFRL.

British Airways installed dosimeters in their Concorde aircraft and in some 747-400 aircraft involved in trans-polar and trans-Siberian flights. It was noted that the doses recorded by these instruments were about 30% higher than the earlier versions of the CARI programs indicated. This data has been used to refine and verify the current version of the program, ie CARI-6.

When those of us involved in talking about space weather effects have talked about space radiation effects on air flights in the past, we have generally discussed the Concorde as a platform in which the crew could be subject to significant radiation doses from solar radiation because of the high latitude (polar) and high altitude (59,000 feet) flights of these aircraft. However, a medical radiation officer for British airways has made two observations in a recent paper (see references):

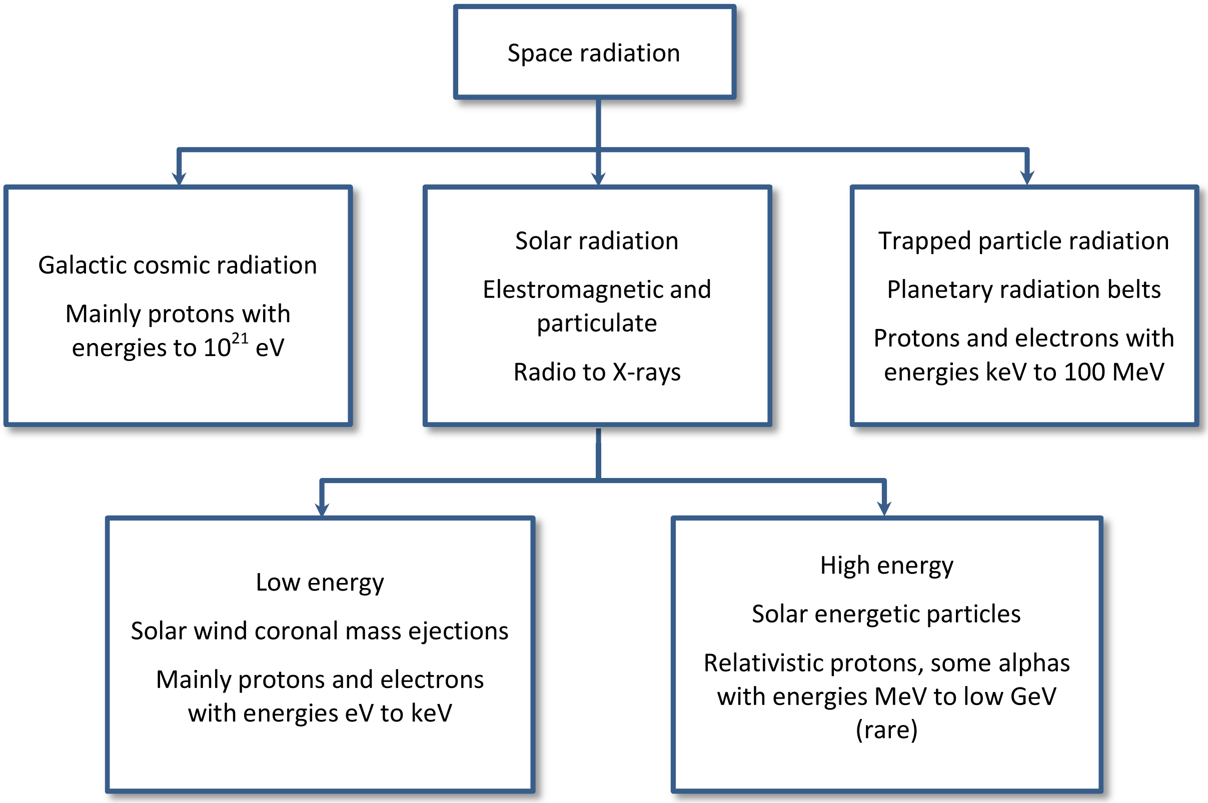
1. Because the 747-400 aircraft is significantly slower than the Concorde, it has at times recorded higher total flight doses than the Concorde, even though it flies at the lower altitude of 41,000 ft (because its total flight time is significantly longer).

2. There is no known instance of a Concorde supersonic transport aircraft (SST) emergency flight plan (to reduce altitude and latitude), which is triggered at a dose rate of 0.5 mSv/hour, being activated, even when an aircraft had been flying during one of the aforementioned 6 ground level events.

Using the CARI-6 program, the radiation absorbed dose was calculated for the following Australian flight:

Melbourne-Perth July 1999 3h50m duration 35,000feet 15.5 µSv (microSv)

It can be seen that this dose is quite small (about 1%) compared to the annual background we receive and compared to the ICRP recommendations. However, a pilot who flies this route once a week (both ways) will double his/her annual dose from GCR. This will take him/her to the recommended ICRP limit for the general public, but still be well below the occupational dose recommended limit.



8. Glossary

AU Astronomical Unit (150 million km) mean distance Earth-Sun
CARI CAMI Radiation Dose Computer Program
CASA Civil Aviation Safety Authority (Australia)
CIMA Civil Aeromedical Agency (part of the FAA)
CR Cosmic Ray or Cosmic Radiation

ESA European Space Agency
eV Electron Volt (a measure of particle energy)
F10.7 Solar ten centimetre radio flux (a good indicator of solar “activity”)
FAA Federal Aviation Administration (USA)
GCR Galactic Cosmic Radiation
GEO Geosynchronous Orbit
GLE Ground Level (Solar Radiation) Event
GSFC Goddard Space Flight Center (NASA)
ICRP International Commission on Radiation Protection
keV thousand eV
LEO Low Earth Orbit
MeV million eV
MOS Metal Oxide Semiconductor (used in Integrated Circuits)
NASA National Aeronautics and Space Administration (USA)
NSSDC National Space Science Data Center (a WDC located at GSFC)
SAA South Atlantic Anomaly
SCR Solar Cosmic Radiation
SEP Solar Energetic Particle
SEU Single Event Upset
SPE Solar Particle Event
SSN (Smoothed) Sunspot Number
SRAG Space Radiation Analysis Group (NASA)
STS Space Transportation System (the NASA Space Shuttle)
WDC World Data Centre/Center

9. References and Comments

9.1 Books and Papers on Space Radiation

“*Space Radiation*” by William R Corliss, US Atomic Energy Commission, 1968
This little book was one of a large series of booklets commissioned by and for the US AEC, and distributed by the US Embassy to many schools around Australia. A very concise easy to read account of space radiation. The first chapter is even entitled “Interplanetary Weathermakers” long before the concept of space weather became popular. May not be so easy to obtain now as the current generation of school librarians has been taught that anything older than 10 years is positively archaic and thus totally (and particularly in the scientific field) useless to anyone.

“*Space Physics*”, edited by DP LeGalley and A Rosen, Wiley, 1964
THE CLASSIC text of space physics. Considers instrumentation used to measure space radiation. Part IV is devoted entirely to “High Energy Radiation in Space”, which includes chapters on the trapped radiation zones (by the West Australian Brian J O’Brien), high-altitude nuclear explosion effects, energetic solar particles, cosmic rays in space and space dosimetry.

MA Shea and DF Smart, “*A Summary of Major Solar Proton Events*”, Solar Physics, v127(#2), pp297-320, 1990.
A comprehensive listing of SPE’s and GLE’s from 1955 to 1986, ie solar cycles 19, 20 and 21.

The November 1988 issue of Proceedings of the IEEE was devoted to papers on Space Radiation and its effects (mainly of electronics). It contained the following comprehensive review of the space radiation environment.

EG Stassinopoulos & J Raymond, “*The Space Radiation Environment for Electronics*”, Proc IEEE, v76 (#11), November 1988

"*Radiation Belts: Models and Standards*", Editors: JF Lemaire, D Heynderickx & DN Baker, AGU Geophysical Monograph 97, 1996
A collection of papers on what the title says. Includes recent satellite results which show formation of a third radiation belt during times of intense solar activity.

The very expensive journal "Advances in Space Research" published by Pergamon has devoted several issues to Space Radiation and its effects. These include:

Vol 19 #5, 1997, "*Cosmic Radiation: Spectra and Composition*"
Vol 17 #2, 1996, "*Near-Earth Radiation Environment Including Time Variations and Secondary Radiation*", edited by MA Shea, W Heinrich and GD Badhwar.
Vol 12 #2-3, 1992 for information on solar activity and STS
Vol 14 #10 & Vol 18 #12 for biological effects of space radiation

"*Radiation Dosimetry vol 3: Sources, Fields, Measurements and Applications*", edited by FH Attix & E Tochilin, Academic Press, 1969
A massive tome which contains one article of over 50 pages entitled "Dosimetry of Radiation in Space Flight" by CA Sondhaus and RD Evans which describes techniques and results from the first decade of space flight.

9.2 Books - Cosmic Radiation

There was a number of books on cosmic radiation published in the 1950's and 1960's that are well worth reading.

The simplest of these was a very readable simple overview:

"*Cosmic Rays*", Bruno Rossi, McGraw-Hill, 1961

Among the better of the more technical texts are:

"*Cosmic Rays*", AW Wolfendale, Newnes, 1963

"*The Cosmic Radiation*", JE Hooper & M Scharff, Methuen, 1958

"*Cosmic Rays*", TE Cranshaw, Oxford, 1963

"*Cosmic Ray Origin Theories*", edited by S Rosen, Dover, 1969
A series of 76 papers in which a diverse range of authors discusses their ideas on how and where GCR originated. Includes the famous acceleration mechanism by Fermi. Contains good experimental data on the nature of the radiation, as well as the theories.

JA Simpson, "*A Physicist in the World of Geophysics and Space*", JGR, v99(#A10), pp19159-19173, October 1994.
A very good reminiscent review paper on cosmic rays by one who was involved from 1947 to the 1960's.

9.3 Books - Radiation Effects

"Genetic Effects of Radiation", CE Purdom, Newnes, 1963
Good description of early history, genetics, mutations in man and genetic radiation hazards in man.

"Low Level Radiation and Living State", Editors NG Huilgol, DV Gopinath, BB Singh, Springer-Verlag, 1994.
A series of 20 articles/papers by a diverse range of authors examining claims and counterclaims for a range of radiation effects. Points out the limited database on which most recommendations

have been made. Draws attention to conflicting studies in many of the areas in question. Good reading.

"Radiation and Health: The Biological Effects of Low Level Exposure to Ionizing Radiations", Editors RR Jones & R Southwood, Wiley, 1987.
Twenty two papers/chapters presenting a multi-viewpoint discussion. Includes initial results from Chernobyl.

"Introduction to Health Physics", H Cember, Pergamon, 1969
One of the best of many books on Health (Radiation) Physics. Mostly on the physical side, but with one chapter concisely summarising the biological effects to substantial radiation doses. Contains details of the equipment used in radiation measurements.

9.4 Web sites on Space Radiation

<nssdc.gsfc.nasa.gov>
<http://ccmc.gsfc.nasa.gov/modelweb/models/trap.php>
The National Space Science Data Coordinated Archive. A World Data Center (WDC) for a vast range of space radiation data. Also freely available here are the models AP-8 and AE-8 for trapped radiation calculations. There are now models AP-9 and AE-9. Links from:
<http://lws-set.gsfc.nasa.gov/radiation_model_user_forum.html>.

<see.msfc.nasa.gov>
The Space Environment and Effects (SEE) Program home page. Located at NASA's Marshal Space Flight Center which is the home of the Space Radiation Analysis Group (SRAG).

<http://www.esa.int/Our_Activities/Space_Engineering_Technology/Space_Environment/Space_environments_and_effects>
The Space Environments and Effects section – a European view.

<http://global.jaxa.jp/>
A Japanese viewpoint.

<http://www-spof.gsfc.nasa.gov/Education/whtrap1.html>
A very brief note on some aspects of the history of discovery and modification of the trapped radiation belts.

<https://www.spenvis.oma.be/help/background/traprad/traprad.html>
Information on trapped radiation and models.

<www.icrp.org>
The International Commission on Radiological Protection.

<http://holbert.faculty.asu.edu/eee560/spacerad.html>
A quick overview of space radiation and its effects.

<http://www.physics.isu.edu/radinf/index.html>
The Idaho State University's has a vast collection of web links on a very diverse range of radiation related issues. A good place to start for radiation information.

9.5 Web sites on Radiation and Aviation

<http://iopscience.iop.org/article/10.1088/0952-4746/28/2/R02/meta;jsessionid=D71C267E44171D02D49882315F7FCE59.c1.iopscience.cld.iop.org>
ICRP Publication 103

<http://www.faa.gov/documentlibrary/media/advisory_circular/ac_120-61b.pdf>

FAA Advisory Circular 120-61. Concerned with crewmember training on in-flight radiation exposure.

<http://jag.cami.jccbi.gov/cariprofile.asp>
The Civil Aerospace Medical Institute of the FAA has a program which estimates the galactic radiation received during a flight or download the program from:
<
https://www.faa.gov/data_research/research/med_humanfacs/aeromedical/radiobiology/cari6/download/>
Site for downloading CARI-6.

9.6 Australian Interest in Aviation Radiation

< https://www.casa.gov.au/sites/g/files/net351/f/_assets/main/fsa/2004/dec/45-47.pdf>
Ian Getley, "Cosmic Gamble", Flight Safety Australia, Nov-Dec 2004, pp46-7
Sue White, "In-Flight Radiation", Flight Safety Australia, Sep-Oct 1999, pp52-3
Both from CASA's bimonthly journal, Flight Safety Australia

< http://www.arpansa.gov.au/radiationprotection/factsheets/is_cosmic.cfm>
< http://www.arpansa.gov.au/pubs/factsheets/FlyingandHealth.pdf>
Australian Radiation Protection and Nuclear Safety Agency information on radiation.

9.7 Notes

1. Note that the NASA trapped radiation belt models (AE-8 for electrons and AP-8 for protons) are only static models. They do not have provision for any solar index as input. Hopefully some new models presently under development will remedy this deficiency.