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COSMIC RAYS
A HAZARD FOR AVIATION?

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When we look out into space at night from the surface of the Earth, we are immediately impressed by the spectacular view of the stars. But what we see with our eyes is a small fraction of the total range of radiation arriving at the Earth. Only as recently as this century has our view of the stars has been greatly extended beyond, and out of, the visible spectrum. Sophisticated instruments routinely allow us to make images of the sky from longer wavelengths than visible light, such as radio waves and infra red, and shorter wavelengths such as ultra violet and x-rays.

Many of the instruments used to make these images at wavelengths beyond the visible light need to be placed in orbit outside the Earth's atmosphere. This is because the atmosphere is very effective at absorbing those wavelengths. Life on Earth has evolved to exploit some of the wavelengths that the atmosphere allows through to ground level. The surface of the Earth has never been exposed to many of the blocked wavelengths, and because life has never had an opportunity to adapt to them, some of those wavelengths are hazardous to life.

The radiation from space is not limited to just the electromagnetic spectrum. A range of non-electromagnetic radiation also arrives at the Earth. One of the most interesting types of the non-electromagnetic radiation is what we now call *cosmic rays*.

Cosmic rays are particles consisting of single atoms of matter. These atoms are usually missing many or all electrons so that usually only the positively charged nucleus of the atom remains. An atom missing one or more electrons is known as an *ion*. Some cosmic rays have been accelerated to very high speeds. Fortunately for us, most of the cosmic rays are stopped by the outer layers of the Earth's atmosphere so that they do not reach the ground. Just as well, because high speed ions can do a lot of damage.

Normally you would not worry about the influence of cosmic rays on your everyday life. But with the advent of mass air travel it is possible to find yourself frequently flying at high altitudes, around 10,000m, above the thickest part of our atmosphere. The thin aluminium walls of the aircraft offer little shielding against the penetrating effects of cosmic rays. We will look at whether you should be worried about this! Not only could cosmic rays damage living organisms, but also some important non-living machines as well. The aim of this lecture is to look at this damage in both the living and non-living.

Characteristics of Cosmic Rays

In 1912 Victor Hess (1883-1964) flew in a balloon above 3,500 m and discovered that charged electroscopes discharged faster at high altitudes than at sea level. This effect was attributed to "atmospheric ionization" and the fact that it increased with altitude led to the conclusion that some kind of radiation must be arriving from space. Hess shared the 1936 Nobel prize in Physics for his discovery. Robert A. Millikan (1868-1953), a scientist better known for his famous oil drop experiment for measuring the charge on the electron, was one of the first to prove this idea. In 1923 he showed that the radiation intensity at a particular depth in a lake at high altitude was the same as in a lake at lower altitude at a shallower depth. The shallower depth being necessary to compensate for the effect of absorption by the atmosphere between the altitudes of the two lakes. With this result proving that the radiation was coming from space, Millikan was impressed by the tremendous penetrating power of the radiation, since to reach beneath the surface of the lakes the radiation had to penetrate through air and water with the equivalent absorbing power of nearly 2m of lead! He therefore assumed that the radiation must have been high energy gamma rays, but he was wrong.

Experiments in the late 1920s and early 1930s detected signs of a *latitude effect* where the intensity of the radiation was found to increase by around 6% towards the magnetic poles of the Earth. This can be expected if the radiation consisted of charged particles. This is because the Earth's magnetic field lines would partially deflect charged particles moving transverse to the field lines, as would be the case for particles arriving at mid latitudes where the magnetic field lines are more parallel to the Earth's surface. Near the poles, the particles could arrive in parallel with the field lines where they curve down following trajectories which could intersect with the Earth's surface. Charged particles moving parallel to magnetic field lines would not experience any deflection. It took Millikan a long time to become convinced that the cosmic rays were charged particles instead of gamma rays. Perhaps this is why we still call them cosmic rays, a name Millikan invented!

Low energy cosmic rays

High energy cosmic rays

The composition of cosmic rays compared to solar system elemental abundances. The light elements lithium, beryllium and boron are far more abundant in cosmic rays because they are created by a process known as spallation which is the breaking apart of heavier nuclei in the interstellar medium by collisions from high energy protons. From Longair.

By the late 1940s, it was clear that the main constituent of cosmic rays was fast protons. However smaller fractions of heavier particles are also present. They are distributed approximately as follows: 85% protons (hydrogen nuclei), 12% alpha particles (helium nuclei), 2% electrons and positrons in proportion about 5:1 and the remaining 1% is made up of heavier nuclei.

The kinetic energy of the particles is distributed over a wide range. A very wide range! The intensity of the energy spectrum of the cosmic rays peaks at about 1 GeV (GeV = 10^9 electron-Volts = one billion electron-Volts) and extends up in energy over more than 10 orders of magnitude. This is a lot of energy. A proton with an energy of 1 GeV is travelling at about 87% of the speed of light. Protons with energies up to about 20 GeV are produced by the Sun during solar flares. But the bulk of these have energies in the MeV range (MeV = 10^6 electron-Volts = one million electron-Volts).

The intensity of cosmic rays does not stay constant. In addition to the solar flares, variations in the Sun's activity changes the interplanetary magnetic field which most strongly affects cosmic rays with energies below 1 GeV. This is called *solar modulation* and the intensity of cosmic rays below 1 GeV can vary by a factor of 10 as a result. When the Sun is at a *high* point of its activity cycle the average cosmic ray intensity is *reduced*. This is because the solar wind produced during high solar activity is more effective in preventing the interstellar flux of cosmic rays from reaching Earth. Very large increases in the flux of cosmic rays can be produced by solar flares.

The cosmic ray intensity above 1 GeV falls off exponentially with energy. Most of these cosmic originate from processes outside our solar system. It is believed that the highest energy cosmic rays were accelerated by supernovae, or by energetic jets from the centres of active galaxies. The intensity of the highest energy cosmic rays is very low: above 10^{19} eV we can expect to detect one particle per square kilometre per year, and above 10^{20} eV about one per square kilometre per century.

When a cosmic ray encounters the upper atmosphere of the Earth, about 20 km above the ground, it soon collides with the nucleus of a gas atom. The electrons in the gas atoms have little effect on such high energy particles. Owing to the large energy of the cosmic ray, a large number of nuclear reactions follow as a result of the collision. A number of nuclear fragments are produced by a process known as *spallation*. These in turn under go additional nuclear collisions. At the same time a great many subatomic particles are produced including electrons, neutrinos, muons, pions and single nucleons (protons and neutrons) as well as x-rays and γ-rays. Some of the particles are unstable and decay to produce still more particles. These all combine to produce an *air shower* of millions of secondary particles that in turn can produce further nuclear reactions. All the particles in the air shower are moving down at close to the speed of light. So at any given instant the air shower is shaped like a disk about 100 m in diameter and about 2 m thick with a central core a few metres in diameter of cascading nuclei. The maximum intensity of the radiation of air showers occurs at about 15 km above the ground, however, the higher energy cosmic ray air showers peak as low as 2 km. If the energy of the primary cosmic ray is large enough, many of the reaction products in the air shower can reach the ground to be detected.

Energy spectrum of cosmic rays at the top of the atmosphere. From Longair.

The products of the air shower can be detected with a variety of techniques. The largest detector in the world is called AGASA (*Akeno Giant Air Shower Array*) located in Japan. This consists of an array of 111 telescopes spread over 100 square kilometres. In December 1993 this detected a cosmic ray with the astonishing energy of 2×10^{20} eV. An even more energetic cosmic ray was detected by the *Fly's Eye* detector in Utah, USA, in October 1991 with an energy of 3×10^{20} eV. Protons with these sorts of energy carry staggering amounts of energy, equal to the total energy of a Dennis Lillee fast bowl cricket ball (5×10^{26} protons and neutrons). Another way of looking at this amount of energy is that it is the same as a house-brick dropped from a height of 1m! As yet the acceleration mechanism of this particle is unknown.

Magnetic fields of the Earth, the Sun or the Galaxy deflect cosmic rays as they travel through space. Charged particles follow spiral trajectories as they are deflected by magnetic fields. Consequently it is not readily possible to determine the origin of cosmic rays by looking back along the direction from which they arrive. In fact it is found that cosmic rays arrive from all directions in space with approximately equal intensity. The distribution is said to be *isotropic*. The radius of the spiral trajectory depends on the strength of the magnetic field and the energy of the cosmic ray. Some representative values are in the following table.

Location	Magnetic field strength (Tesla)	Spiral radius (m) 1 GeV proton	Spiral radius (m) 10^{20} eV proton
Earth's surface	1×10^{-4}	5×10^{4}	3×10^{15}
Interplanetary space	5×10^{-9}	1×10^{9}	6×10^{19}
Interstellar space	3×10^{-10}	2×10^{10}	1×10^{21}

Compare: radius of Earth's orbit = 1.5×10^{11}m
1 light year = 1×10^{15}m

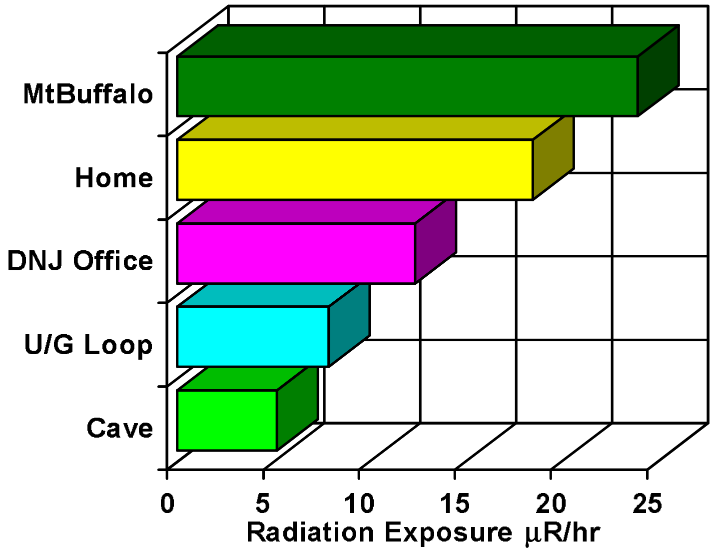
From the honours thesis of T.H.K. Irving

Clearly the rare highest energy particles are not significantly affected by the magnetic fields in space. By careful measurement of the time when particles in an air shower reach each detector in an air shower detector array it is possible to reconstruct the original trajectory of the primary cosmic ray particle responsible for the air shower. In the case of the very high energy cosmic rays, astronomers have looked with optical telescopes out along these directions, but so far nothing unusual has been found that could account for how the particles obtained their energy.

Cosmic Rays near the Surface of the Earth

The flux of ionizing radiation in an air shower can readily detected with simple apparatus. A company in the USA makes a small Geiger tube that can be plugged into the serial port of a laptop computer. A Geiger tube consists of a metal cylinder capped with a mica window and containing a low pressure gas mixture. A wire running down the centre of the tube is connected to a high voltage power supply. When ionizing radiation passes through the tube, it momentarily ionizes the gas allowing a small pulse of current to flow from the high voltage wire to the wall of the tube. This is detected by external circuitry and the pulses are fed into the computer to be counted.

Measurements by the author, shown in the histogram below, have compared the radiation levels in a cave in Naracoorte in South Australia, in the Melbourne underground rail loop, in his office, at home and on the top of Mt Buffalo in the Victorian Alps. The significant differences are mainly due to the differing amounts of cosmic ray shielding in each of these places. These were, respectively, 15 m of rock, 5-10 m concrete, 2-5 m concrete, roof tiles and the lack of about 1,500 m of atmosphere. The units of radiation exposure are discussed in more detail below.

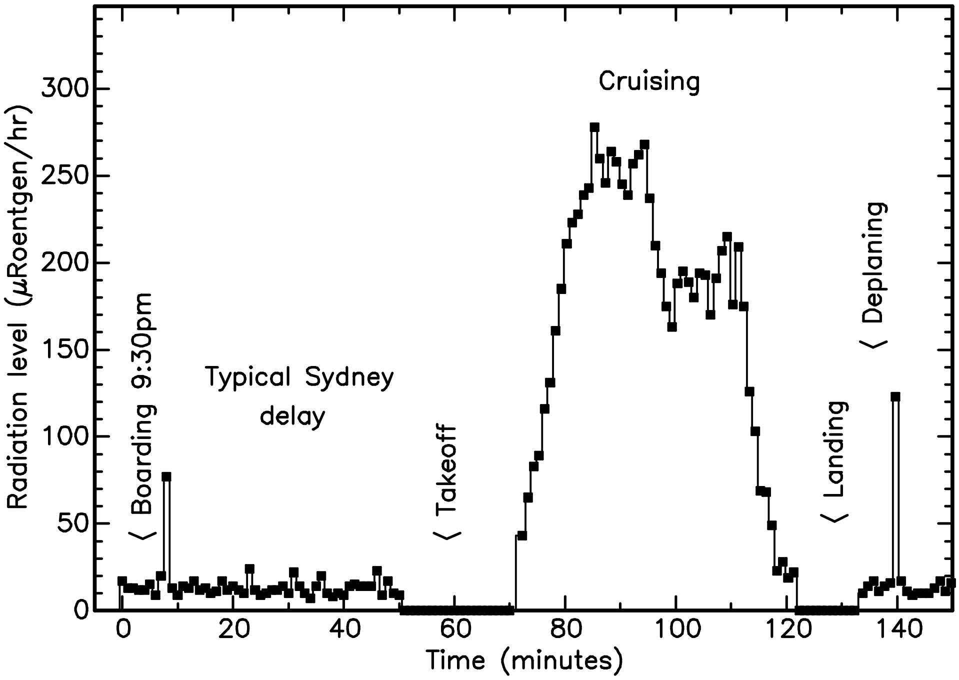


Radiation measurments by the author in a variety of locations with different shielding from cosmic rays.

These measurements clearly show that shielding has a dramatic effect on the level of the cosmic ray background. So what happens when the shielding is reduced still further by rising above the thickest part of the atmosphere in an aircraft? The increase in the cosmic ray background radiation at an altitude of 10,000 m in a domestic aircraft is dramatic. The figure on the next page shows a measurement of the radiation exposure in the passenger cabin during a domestic flight from Sydney to Melbourne. As with all electronic devices in the possession of passengers, the counter and the computer cannot be used during take-off and landing. The remarkable increase in the radiation level from cosmic rays is clearly seen.

Most sub-sonic commercial aircraft, like the Airbus or the Jumbo jet, fly at altitudes between 9 and 12 km (29,500 and 39, 00 ft) in altitude. Due to the absorbing effects of the atmosphere, the radiation dose from cosmic rays increases roughly exponentially with altitude. The dose rate at 15 km is about twice that at 10 km. A Concorde aircraft flies at about 17 km in altitude, well above that of the sub-sonic aircraft. Thus the Concorde passengers are exposed to more that twice the dose for a given length of time during their journey. Of course, the Concorde has a cruising speed of 2,150 km/hr (Mach 2) is much faster than that of a 7 7- 00 Jumbo jet which is "only" 930 km/hr (Mach 0.85). So to cover a given distance the Concorde passengers spend less than half the time in flight compared to the 7 7.

Radiation dose rates 5 cm deep in a 30 cm slab of tissue at solar minimum. From CACAQ.



Radiation level measured in the passenger cabin of a Qantas Airbus on a flight from Sydney to Melbourne. Note that the measuring instrument was switched off during takeoff and landing. The reduction in the level at 95 minutes is probably due to a change in altitude that occurred at the same time.

Impact of Cosmic Rays on Matter

Most primary cosmic radiation and secondary radiation in the air showers are absorbed in the atmosphere before reaching the ground. But what happens if cosmic rays collide with a person or a machine? When a high energy charged particle collides with a lump of matter, it begins to slow down and loose energy. The rate at which it does this is called the *stopping power* of the matter. The stopping power depends on the characteristics of the matter and the energy and type of the charged particle. It usually does not matter if the charged particle carries any electrons with it before impact, since these will be stripped away on impact, so, in the case of cosmic rays, only the interaction of the fully ionized nucleus need be considered.

As a high energy particle slows down, it first interacts mainly with the electron clouds surrounding the atoms and molecules in the matter. Because of its initial high speed, the probability of interaction with the relatively tiny and dense nucleus is low. Since the electron clouds are very diffuse compared to the nucleus, the amount of energy deposited is relatively small. In this initial part of the trajectory through a lump of matter, the high energy particle is said to undergo *electronic stopping*. If the particle can be slowed enough by this process to allow it in interact with the nuclei of the solid themselves it will then begin to loose energy much faster. This is called *nuclear stopping*. During this process the particles dissipate their remaining energy by many collisions with the nuclei of the solid. As a consequence, the solid is greatly disrupted in the vicinity. This volume of disrupted material is at the *end of range* of the original particle which is where it eventually comes to a stop. The range of the particle is the distance it can travel in a given material before it is brought to a stop. This can be many metres for a high energy particle.

Range of a 1 GeV proton in various materials

Material	Interstellar space	Air	Water	Human muscle	Aluminium or Silicon	Lead
Range	~10^{24} m	3000 m	3.2 m	3.1 m	1.5 m	0.53 m

Calculations by program TRIM

The carried and deposited in matter by ionizing radiation, including that from the primary and secondary cosmic ray showers, may be measured using radiation dose units. There are two useful concepts. The first is the concept of *radiation exposure,* or dose. Units that describe radiation exposure describe the amount of energy available from a source of radiation. This energy can be used to ionize air. An example is the unit Roentgen which is defined:

$$1 \text{ Roentgen} = 1 \text{ R} \equiv 8.78 \text{ mJ/kg of dry air} = 2.58\times10^{-4} \text{ Coulomb/kg of dry air} = 1. \quad 1\times10^{12} \text{ ion pairs/kg}$$

This is more usually expressed as a dose rate such as R/hr. The second concept is that of *absorbed dose* where the radiation is now used to deliver energy to a solid. The SI unit for this is the Gray, which for biological tissue may be defined as:

$$1 \text{ Gray} = 1\text{Gy} \equiv 1 \text{ Joule/kg of exposed tissue } (\approx 100 \text{ R for biological tissue})$$

So approximately 100 Roentgens of exposure leads to 1 Gray of absorbed dose. An older unit, still in use, is the rad:

$$1 \text{ Radiation Absorbed Dose} = 1 \text{ rad} = 0.01 \text{ Gy } (\approx 1 \text{ R for biological tissue})$$

An additional unit of absorbed dose is necessary to account for the differing effects ionizing radiation has on biological tissue. This is because for the same exposure, charged particles do more damage than the same dose of x-rays or γ-rays. This leads to the definition of the SI unit Sievert:

$$1 \text{ Sievert} = 1 \text{ Sv} \equiv \text{QF}\times(1 \text{ Gy}) \; (\approx 100 \text{ R for biological tissue for QF}=1)$$

Where QF stands for *Quality Factor* (loosely equivalent to the *Relative Biological Effectiveness* factor, RBE) which is the factor by which the damage done exceeds that of x-rays or γ-rays. Some representative values are given in the table:

Quality Factor for several types of radiation

X-rays & γ-rays	Electrons (β particles)	He nuclei (α particles)	Slow neutrons	Fast neutrons and protons	Heavy ions
1.0	1.0	10 – 20	4 – 5	10	20

An equivalent older unit, still in use, is the rem:

$$1 \text{ Roentgen Equivalent Man} = 1 \text{ rem} = 0.01 \text{ Sv} = \text{QF}\times\text{rad} \; (\approx 1 \text{ R for biological tissue and QF}=1)$$

To put these numbers into perspective, the table on the next page lists the radiation exposures you are likely to experience in your everyday life over the course of one year. These numbers should be taken only as a rough guide. The University of Melbourne follows rules set down by the International Commission on Radiological Protection (ICRP) which are normally endorsed by the Australian National Health and Medical Research Council (NHMRC). For members of the general public, the exposure limit is set to 1 mSv per year. I assume this means 1 mSv from all artificial sources of radiation, since the

Sources	Dose in mSv/yr (mSv=10^{-3} Sv)
Natural	
cosmic radiation, sea level	0.3
soil, rock, building materials	0.3
human tissue (^{40}K, ^{226}Ra)	0.4
radon (^{222}Rn) in the air	2
Total	**3**
Artificial	
medical & dental x-rays	0.4
nuclear medicine	0.1
nuclear power	0.01
TV tubes, industry	0.02
nuclear test fallout	0.04
Total	**0.6**
Total from all sources	3

Data adapted from Merken and Ackland.

natural dose can exceed this value as seen in the table. It is considered that this figure produces minimal statistical health risks. For staff who work with radiation, the occupational dose is set at 20 mSv per year for a whole body dose.

By comparison with the figures in the table, absorption of a dose of 3 Sv (=3000 mSv) of γ-rays would be enough to cause death in about 50% of an exposed population. This corresponds to a total absorption of energy, determined by the definitions given above, of (3 Sv)×(1 QF)×(1 J/kg) = 3 J/kg in the body. This is a remarkably small amount of energy. If absorbed by water this would produce a temperature rise of only 700 millionths of a degree Celsius. Macroscopic objects carry far more energy. For example a 10 g rifle bullet travelling at the speed of sound (300 m/s) carries 450 J of kinetic energy.

Effects of Cosmic Rays on Living Organisms

The most critical effects cosmic rays have on living organisms, as with any other form of low level ionizing radiation, is the damage done to the DNA molecules. If cosmic radiation ionizes an atom that makes up part of a DNA molecule several types of damage can result including: a double strand break, the deletion of a base from one base pair in the chain or chemical cross-linking in the two strands. It is possible for an indirect process to also cause these types of damage where a free radical created by the radiation attacks a DNA molecule. These defects can be repaired without ill effects, however sometimes to repair is not successful.

A DNA molecule that has not been repaired or misrepaired leads to a damaged chromosome that can lead to cancer. The statistical nature of the radiation damage means that the precise outcomes associated with a given exposure to radiation cannot be defined accurately for a single person. A further difficulty is that the risk depends not only on the induced damage, but also the efficiency of the repair mechanisms which varies between people.

Using the ICRP guidelines of 1 mSv per year, we can determine the risk of cosmic rays when flying. From the measurements of the cosmic rays exposure in the aircraft shown above, a maximum exposure rate of about 300 μR/hr was recorded during the flight. This translates into an approximate absorbed dose rate of 0.003 mSv/hr using the assumption that 1 R is equivalent to 0.01 Sv. This dose rate is equal to 2 mSv/yr. Therefore you would need to fly for a total of more than 300 hours each year to accumulate 1 mSv per year from this source! The table below gives the dose rates for different scenarios. Flying higher in supersonic jets reduces the number of flying hours by one third to reach the dose limit and astronauts have a particularly hard time, especially during times of solar flares. However, my conclusions from my own measurements presented here and those available in the literature, is that cosmic rays do not represent a significantly greater danger to one's health than any other form of radiation in the environment such as that from radon, or medical x-rays. In the flying I have done, I have considered the risks involved to be insignificant compared to the benefits I have gained from the flight!

	Approximate Cosmic Radiation Dose			
Condition	Sea level	Subsonic jet at 10km altitude	Supersonic jet at 18km altitude	Astronaut*
Dose rate (mSv/yr)	0.5	2	100	200
Dose rate (mSv/hr)	0.0001	0.003	0.01	0.02
Flying time for 1mSv	2 years (!)	300 hours	100 hours	50

*includes galactic cosmic rays only and ignores contribution from Van Allen belts (~3mSv per transit) and solar flares (~1000mSv per flare)

Table adapted from A. Gregory and R.W. Clay

Effects of Cosmic Rays on Computers

So far we have looked at the radiation dose on the people in the aircraft. However the modern aircraft is controlled by a significant number of computers and other electronic hardware. Radiation, both electromagnetic and otherwise, can affect electronic circuits. It is the purpose of this discussion to focus on the effects of the passage of charged particles, such as those from air showers, through electronic devices. This topic has been subject to intensive study around the world, not only for aviation, but also for satellites in Earth orbit and for interplanetary spacecraft.

An electronic device, in essence, consists of alternating layers of semiconductor material, arranged in intricate patterns, to make up useful circuits such a memory cells, central processor units and sensors. Individual devices are composed of *circuit elements*, such as transistors, resistors, capacitors, etc, all integrated into a single crystal of a semiconductor crystal, most commonly silicon. The scale of the circuit elements in modern devices is approaching 0.35 µm in diameter. During use, these tiny circuit elements store electric charge that is responsible for maintaining logic levels, or processing information. A key feature of many circuit elements is that they contain a layer of semiconductor material doped with a group 3 atomic element in contact with a layer of material doped with a group 5 atomic element. This forms a *p-n junction,* myriads of which are responsible for switching currents between circuit elements as information is processed.

Formation of a depletion region around a p-n junction in a microelectronic device. From Serway.

A p-n junction has the special attribute that a built-in electric field exists across the junction. The volume of this electric field is typically small, extending within about 0.5 µm of the junction. This field arises from the exchange of unpaired electrons from the group 5 atomic elements to the group 3 atomic element so that both can end up with a total of 8 outer shell electrons in the form of covalent bonds with their surrounding 4-valence silicon atoms. Since the "spare" electron associated with the group 5 atomic element and the "hole" associated with the group 3 atomic element can be used to carry electric current across the junction, the region where the electric field exists is called the *depletion region*. This is because the spare electrons migrate to fill in the holes. It is given this name because the region is thus depleted of free charge carriers as a result of the built-in electric field. External bias voltages applied across the junction can extend the volume of the depletion region.

As we have seen, a high energy cosmic ray can easily penetrate thick layers of matter. As it does so it deposits energy in the form of ionization and displaced atoms. The ionization typically consists of electrons freed from positive ions left behind in the solid. Usually, these free electrons will eventually recombine with the ions leaving only the displaced atoms as a record of the passage of the ion. However the situation is different if the cosmic ray passes through a depletion region of a microelectronic device. In this case the built-in electric field sweeps the free electrons away from the ions and into the external circuit elements before all of them have a chance to recombine. The result of this is that the swept out charge appears as a small pulse of current in the external circuit.

In fact solar cells and semiconductor radiation detectors are constructed to exploit this phenomenon. In a solar cell, sunlight creates the free charge carriers within a depletion region of a p-n junction which are then swept out into an external circuit. In a semiconductor radiation detector, a large depletion region is created by an external bias voltage in a large crystal that is designed to be big enough to completely stop the incoming radiation of interest. The entire kinetic energy of the incident radiation is converted into a current pulse in an external circuit.

Depletion region

Effect of a cosmic ray ion strike on a depletion region of a p-n junction in a microelectronic device. From Sexton.

Of course computers and other electronic circuits are not intended to be used as radiation detectors! A problem arises if the current pulse from a cosmic ray induced ionization is sufficiently large to alter the state of the surrounding circuits within a computer memory or control circuit. The result of a cosmic ray strike on an integrated circuit produces two types of errors that are of interest. One type is called a "soft" error in which only a logic level changes and no permanent damage to the circuit results. This is called *a single event upset* or SEU. Such errors can corrupt the information stored in computer memories or cause algorithms to return incorrect results. An even more serious error is a "hard" error where permanent damage results. This can occur of the cosmic ray strike occurs through the dielectric of a tiny charged capacitor that makes up part of a memory cell. The capacitor can suddenly discharge through the column of ionization that bridges the dielectric causing the circuit element to rupture from overheating. Another type of hard error is known as *latchup*. In this case the column of ionization from a cosmic ray strike in a device serves as a momentary additional electrical connection between different parts of the device causing the circuit to enter an unintended state, often involving a damaging heavy flow of current. The device becomes latched in the unintended state and even if irreversible damage does not occur, it cannot recover until it is powered off and on again.

As device geometries shrink further, the electronic circuits become more and more susceptible to these sorts of errors. In the early '70s, about 50 pJ (1 pJ = 1×10^{-12} Joules = MeV) of energy was required to switch a logic level in a circuit. This has now shrunk to less than 0.5 pJ which is only 10^6 charge carriers crammed into the 10 square micrometre area of the circuit element. The design of devices which are *radiation hard*, that is resistant to upsets and latchups, is a major priority for circuits used in critical applications.

Single event upset image of a computer memory integrated circuit obtained by deliberately scanning the circuit with a MeV proton beam. From Doyle.

As part of the design work towards fabricating devices that are radiation hard, the nuclear microprobe group in the Microanalytical Research Centre at the University of Melbourne has been involved in the investigation of SEU events in computer memory cells. A proton beam is directed onto various locations within an integrated circuit while a computer monitors the state of the circuit. The computer records the locations where the proton beam causes the circuit to upset. In this way the most vulnerable regions of the circuit can be located. This technique has many other applications as well, including the study of *charge recombination* in solar cells. Charge recombination is a process whereby part of the photovoltaic current induced in the cell does not get swept out of the depletion region into the external circuit as it is supposed to, but gets trapped and annihilated at defects instead. This process can rob solar cells of more than 15% of their efficiency.

Radiation hard electronics

The probability of a SEU event or a latchup causing a problem in the electronic circuits of a commercial aircraft is low, since they fly below the altitude where the circuits will be greatly exposed to the high intensity primary flux of cosmic rays. Most of the radiation experienced at altitudes around 10 km is due to secondary particles in the air showers which are less effective at generating ionization in the depletion regions of the devices. Higher altitude aircraft and satellites need careful attention to circuit design to minimise problems.

Several strategies for hardening microelectronic devices against the effects of cosmic ray strikes are possible. Software based procedures can be devised that continually monitor computer memories for integrity and correct errors as they occur. This can impose heavy burden on the central processor unit.

Another approach is to design the circuits to begin with to make them less susceptible to cosmic ray strikes. This can be accomplished with ***silicon on insulator*** (SoI) technology. SoI involves growing a thin layer of single crystal silicon over a thick insulating layer. The circuit elements are then fabricated in this thin layer. As the resulting devices are thin, and isolated from the substrate, the ionization generated by a cosmic ray strike cannot diffuse back into the depletion regions of the devices. Also, it may be possible in the future to fabricate microelectronic devices from more robust materials such as silicon carbide or diamond. In these materials the electronic band gap of the crystal lattice is considerably wider than in silicon (~5 eV compared to ~1 eV). This means considerably more energy is required to generate free electrons that interfere with the normal functioning of the device. Less sophisticated approaches simply depend on redundant systems so if one device returns an erratic result it is ignored in favour of the other systems which would be unlikely to suffer a simultaneous strike.

Upset thresholds as a function of dose rate for some 1978 vintage integrated circuits (data from Messenger and Ash).

Origin of Cosmic Rays

Although the precise mechanisms of how the highest energy cosmic rays were accelerated to their very high energies is still a matter of intense debate, the mechanisms for the lower energies have been discovered. These mechanisms almost always involve regions of moving magnetic fields. Charged particles "bouncing" between rapidly moving regions of changing magnetic field strength can be accelerated to very high energies. On a smaller scale, the mechanisms are observed at work in the magnetosphere's of the Earth and the other planets. In fact the interstellar medium itself is now recognised as being a very turbulent magnetic environment, driven to a large degree by the magnetic shockwaves radiating away from supernovae.

Late in 1995, evidence was provided by the Japanese/US x-ray astronomical satellite (ASCA) that two regions located symmetrically about a rapidly expanding supernova remnant (the supernova of 100 AD) were producing intense synchrotron radiation. This radiation is associated with electrons spiralling at close to the speed of light in strong magnetic fields. Within these fields, protons and other ions bounce back and forth within turbulent regions and acquire enormous kinetic energies, up to about 10^{15} eV, in a process originally proposed by Enrico Fermi (1901-1954) in 1949. The ions from this and other supernovae escape and find their way out into space where they become cosmic rays.

The higher energy cosmic rays, above 10^{15} eV, even more powerful acceleration mechanisms appear to be necessary and for these we must look outside our own galaxy. Jets of high speed matter are often associated with active nuclei of some types of galaxies where immense black holes are believed to exist.

It is possible that these are involved in the acceleration of the highest energy cosmic rays. However the precise mechanisms remain to be fully understood.

Cosmic rays remain the only source of material that comes to us from outside out solar system and even outside our galaxy. They carry energies that are well beyond anything possible with the largest particle accelerators built on Earth. The nuclear reactions they produce in our atmosphere provide valuable information about the fundamental structure of matter. Therefore cosmic rays provide information about the universe on both the smallest and largest scales. The understanding of these structures continues to be a fascinating and elusive goal.

References

L. Ackland, *Public Health: The Radiation Question*, in World Book Science Year 996, World Book Inc, 996.

M.B.H. Breese, D.N. Jamieson and P.J.C. King, *Materials Analysis using a Nuclear Microprobe*, Wiley 996.

Committee on Airliner Cabin Air Quality (CACAQ), *The Airliner Cabin Environment: Air Quality and Safety*, National Academy Press, 986.

B. Doyle, K.M. Horn and F.W. Sexton, *Microbeam Single Event Upset Testing*, Presented at the RADSCON-96 shortcourse on space environments and simulations for SEU tests, April 2 996.

A. Gregory and R.W. Clay, *Cosmic Radiation*, in CRC Handbook of Chemistry and Physics, 74th edition, 994, D.R. Lide and H.P.R. Frederikse, Eds. p - 40.

V.L. Grinzburg, *The Astrophysics of Cosmic Rays*, Israel Program for Scientific Translations, 969.

T.H.K. Irving, *Cosmic Ray Imaging: Feasibility and System Design*, Honours Thesis, University of Melbourne, School of Physics, 995.

D.J. Kevles, *Robert A. Millikan*, Scientific American, Jan 979, p 8.

K. Koyama, et al., Nature 78 995, p255, quoted in *Evidence of Cosmic Ray Acceleration*, Physics Update in Physics Today, Feb 996, p9.

J. Linsley, *The Highest Energy Cosmic Rays*, Scientific American, July 978, p48.

M.S. Longair, *High Energy Astrophysics, Vol. 1 & 2*, Cambridge University Press, 994.

M. Merkin, *Physical Science with Modern Applications*, Sanders, 99 .

G.C. Messenger and M.S. Ash, *The Effects of Radiation on Electronic Systems*, Van Nostrand Reinhold, 986.

D. Morrison, S. Wolff and A. Fraknoi, *Abell's Exploration of the Universe, 7th Edition*, Saunders, 995.

R.A. Serway, C.J. Moses and C.A. Moyer, *Modern Physics*, Sanders, 989.

F.W. Sexton, *Measurement of Single Event Phenomena in Devices and ICs*, Sandia National Laboratories, Albuquerque, NM, USA.

M.M. Shapiro and J.P. Wefl, eds, *Genesis and Propagation of Cosmic Rays*, NATO ASI Series C, D. Reidel Publishing, 987.

United Nations Scientific Committee on the Effects of Atomic Radiation, *Sources and Effects of Ionizing Radiation*, UNSCEAR 99 Report to the General Assembly, 99 .

A.C. Upton, *The Biological Effects of Low Level Ionizing Radiation*, Scientific American, Feb 982, p29.

J.F. Ziegler, *TRIM: The Transport of Ions in Matter*, IBM-PC computer program, described in J.F. Ziegler, J.P. Biersack and U. Littmark, *The Stopping and Range of Ions in Solids*, Pergamon, 985.

Aware Electronics, *RM-60 Micro-Roentgen Radiation Monitor*, P.O. Box 4299, Wilmington DE 9807, U.S.A.

Web Sites (July 1996)

`http://www.british-airways.com`
Information about the cruising speed of commercial aircraft, as well as some good pictures.

`http://www-ik1.fzk.de/www/kascade`
Information about the Karlsruhe Shower Core and Array Detector for research into the air showers initiated by high energy cosmic rays.

`http://www.icrsun.icrr.u-tokoyo.ac.jp/as/project/agasa.html`
The Akeno Giant Air Shower Array, the largest air shower array in the world. Site includes information about the highest energy cosmic rays ever detected.

`http://www.physics.adelaide.edu.au/astrophysics`
Links to many sites concerned with cosmic ray research in Australia and overseas. Includes information about the Pierre Auger project, a giant cosmic ray detector now being designed.

`http://www.physics.utah.edu/research/astro.html`
The headquarters of the “Fly’s Eye” cosmic ray air shower detector at the University of Utah

`http://www.sover.net/~radcount/news95.html`
A discussion paper aimed at aviation professional on radiation effects on flight crew.

`http://www.maui.net/~diana/radiat.html`
An extract from a popular book which includes a brief discussion of inflight radiation.

`http://fourmilab.ch/documents/ohmygodpart.html`
A site with much of interest in astronomy, this document is a discussion of the highest energy cosmic ray ever detected.

`http://www.fcaglp.unlp.edu.ar/~spaoli/cosmos95/0095.html`
A press release with information about the possible origin of high energy cosmic rays.

`http://www.dias.ie/c4/resources.html`
A comprehsive list of links to many places in the world involved with cosmic ray research.