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Cosmic Radiation

By Dr. Anthony J. Keane*

Introduction to Cosmic Radiation

The planet Earth orbits the Sun in what is often considered to be empty space but is in fact full of very small charged particles speeding in all directions. The situation can be compared to the Earth having to constantly travel in a light shower of rain and with the atmosphere acting like an umbrella. The 'rain' is made up of charged particles called 'Cosmic Rays'. The name *cosmic ray* was given long ago to invisible ionising radiation that could mysteriously discharge an electroscope even when the electroscope was heavily insulated. Early scientists quickly established a relationship between the rate of charge loss and altitude, i.e. a gold-leaf electroscope would lose its charge much faster at the top of a mountain than at sea level, [1]. Many clever experiments led scientists to suspect that invisible radiation was coming from the sky and penetrating the electroscope thus neutralising the charge, [2]. The nature of the ionising radiation and its origin has remained one of the primary areas of research in astrophysics over the last hundred years. This article gives an overview of elemental cosmic radiation and also presents the results from an experiment to measure the upper charge regions of the cosmic radiation spectrum. This work was done at the Dublin Institute of Advanced Studies in a project called the Ultra Heavy Cosmic Ray Experiment, (UHCRE). This experiment involved an extensive study conducted during the 1980s and 1990s with the co-operation of the European Space Agency, which built the satellite (LDEF) and NASA, which deployed and retrieved LDEF from low Earth orbit, [3].

What are Cosmic Rays

In explaining what constitutes elemental cosmic rays we need to recall the periodic table. This is an ordered list of the elements that make up all matter in the Universe. The first element is Hydrogen, then Helium, Lithium, and so on. Each element in the list has a number according to the number of protons it contains. Hydrogen has one proton, Helium has two protons, Lithium has three protons and so on, see figure 1.

The proton is a positively charged particle and to make an atom (which is neutrally charged) the protons need an equivalent number of negatively charged particles called electrons. Each electron has an equivalent charge magnitude to the proton but electrons are very much smaller in size than protons, so much so, that it takes almost 2000 electrons to be equal in mass to one proton.

The periodic table is organized into 7 periods and 18 groups. The elements are color-coded by groups: Group 1 (IA) is orange, Group 2 (IIA) is purple, Groups 13-18 (IIIA-VIIIA) are green, and Groups 3-12 (IIIB-VIIB) are blue. The Lanthanide Series (La-Lu) and Actinide Series (Th-Lr) are shown in grey at the bottom.

| Period | 1 IA | 2 IIA | 3 IIIB | 4 IVB | 5 VB | 6 VIB | 7 VIIB | 8 VIII | 9 VIII | 10 VIII | 11 IB | 12 IIB | 13 IIIA | 14 IVA | 15 VA | 16 VIA | 17 VIIA | 18 VIIIA | |
|--------|-------------|-------------|--------------|-------------|-------------|------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 1 | H (1.01) | He (4.00) | | | | | | | | | | | B (10.81) | C (12.01) | N (14.01) | O (16.00) | F (18.99) | Ne (20.18) | |
| 2 | Li (6.94) | Be (9.01) | | | | | | | | | | | Al (26.98) | Si (28.09) | P (30.97) | S (32.07) | Cl (35.45) | Ar (39.95) | |
| 3 | Na (22.99) | Mg (24.31) | | | | | | | | | | | Ga (69.72) | Ge (72.64) | As (74.92) | Se (78.96) | Br (79.90) | Kr (83.80) | |
| 4 | K (39.10) | Ca (40.08) | Sc (44.96) | Ti (47.88) | V (50.94) | Cr (51.99) | Mn (54.94) | Fe (55.85) | Co (58.93) | Ni (58.69) | Cu (63.55) | Zn (65.38) | Cd (112.41) | In (114.82) | Sn (118.71) | Sb (121.76) | Te (127.60) | I (126.91) | Xe (131.29) |
| 5 | Rb (85.47) | Sr (87.62) | Y (88.91) | Zr (91.22) | Nb (92.91) | Mo (95.94) | Tc (98.91) | Ru (101.07) | Rh (102.91) | Pd (106.42) | Ag (107.87) | Cd (112.41) | In (114.82) | Sn (118.71) | Sb (121.76) | Te (127.60) | I (126.91) | Xe (131.29) | |
| 6 | Cs (132.91) | Ba (137.33) | La* (138.91) | Hf (178.49) | Ta (180.95) | W (183.85) | Re (186.21) | Os (190.23) | Ir (192.22) | Pt (195.08) | Au (196.97) | Hg (200.59) | Tl (204.38) | Pb (207.2) | Bi (208.98) | Po (209) | At (210) | Rn (222) | |
| 7 | Fr (223) | Ra (226) | Ac- | Rf (261) | Db (262) | Sg (266) | Bh (264) | Hs (277) | Mt (268) | *** | *** | *** | | | | | | | |

| | | | | | | | | | | | | | | |
|--------------------|-------------|-------------|-------------|----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Lanthanide Series* | Ce (140.12) | Pr (140.91) | Nd (144.24) | Pm (145) | Sm (150.36) | Eu (151.96) | Gd (157.25) | Tb (158.93) | Dy (162.50) | Ho (164.93) | Er (167.26) | Tm (168.93) | Yb (173.05) | Lu (174.97) |
| Actinide Series- | Th (232.04) | Pa (231) | U (238.03) | Np (237) | Pu (244) | Am (243) | Cm (247) | Bk (247) | Cf (251) | Es (252) | Fm (257) | Md (258) | No (259) | Lr (260) |

Figure 1: Periodic Table of the Elements

This means that the mass of electrons do little to change the mass of a neutral atom. Electrons orbit the central positive core (called the nucleus) of an atom in discrete shells. The nucleus contains protons and neutrons. Neutrons are particles similar in size to the proton but are neutrally charged. The neutrons are used to prevent the nucleus of an atom from breaking up due to the repulsive positive charges of the protons. Elemental cosmic rays consist of all the elements from the periodic table and these elements, (or particles) can exist in varying degrees of ionisation. An ionised particle is where one or more electrons have been removed from the neutral atom giving the atom a net positive charge.

Origin of Cosmic Radiation

To talk about the origin of cosmic rays we need to look at how matter is created. In the beginning of the Universe, according to the Big Bang theory, there initially existed just energy at very high temperatures, too high for matter to exist. As cooling occurred, basic constituents of matter were formed, like electrons and protons. Mutual attraction between the particles led to the formation of simple atoms like hydrogen, helium, and their isotopes. To create atoms bigger than Lithium requires a mechanism that can add protons to the nucleus of an atom but the problem is that a nucleus has a net positive charge and easily repels any

approaching proton. The proton needs sufficient energy to overcome the repulsion force of the nucleus to gain entry. Neutrons on the other hand do not experience any repulsion from positively charged nuclei. Also neutrons can change into protons while inside the nucleus thus allowing one element to change into another element (the dream of the alchemists).

In the beginning of the Universe there was just Hydrogen, Helium and their isotopes that formed into clouds. When a cloud had sufficient mass it would collapse into a denser cloud and so on until the temperature at the centre of the cloud was high enough to start a fusion reaction and thus a star is born. A star has a life cycle; it is born, lives by burning its stellar material and dies when the forces of radiation that hold-up a star can no longer resist the gravitational forces that are compressing the star. This creates a cycle in which stellar material is reused again and again in a true recycling process. Many stars are good at producing elements from Lithium up to the iron group, [4]. To make bigger elements than the iron group requires a more energetic process than found in the centre of a star. One way sufficient energy is supplied is when a star explodes. Stars come to the end of their life in many different ways but the most impressive way is when the star explodes with the brightness of a thousand galaxies called a supernova, [5]. Supernova can be so bright that we can easily see them with the unaided eye, even during daytime hours. Supernova cause the individual parts (the atoms and molecules) to be split apart by the tremendous energy and flung into space with a great velocity. During this process there is the opportunity for new elements to be created with higher proton numbers than was originally in the star itself through a process called nucleosynthesis. Stars are factories for matter production and primary sources of cosmic rays. Other sources that contribute to cosmic radiation are partially ionised particles that gain energy by passing close to our Sun and particles and dust grains accelerated at the edge of the Solar System (called anomalous cosmic rays), [6].

Cosmic Ray Energies

Each cosmic ray source is distinguished by the energy (how fast the cosmic ray is travelling) of the cosmic rays. Energies are measured using a unit called the electron volt, eV. An electron volt is the energy that an electron gains when it travels through a potential of one volt. You can imagine that the electron starts at the negative plate of a parallel plate capacitor and accelerates to the positive plate, which is at one volt higher potential. Numerically one eV equals 1.6×10^{-19} joules or a joule is 6.2×10^{18} eV. For example, it would take 6.2×10^{20} eV/sec to light a 100 watt light bulb.

Space is essentially empty so there is little material that can get in the way and slow down the particles from supernova as they are scattered throughout the Universe. Some of these

particles will become seed material for other stars while some remain travelling through the Universe moving with a high velocity approaching the speed of light. Interactions with magnetic fields add further energy to the particles but the exact mechanism that allows particles to achieve such high velocities, such as 10^{21} eV, is not fully understood even today.

Solar cosmic rays generally have low charge and low energy (~ 1 MeV) and are about half ionised. Anomalous cosmic rays have energies around 10GeV and are singly ionised. Galactic cosmic rays have energies in the approximate range of 1GeV to 10^{15} GeV and are fully ionised. Figure 2 shows a log-log plot of the flux of cosmic rays bombarding Earth as a function of their energy per particle. Researchers believe cosmic rays with energies less than $\sim 3 \times 10^{15}$ eV come from supernova explosions while the origin of cosmic rays with energetic more than 10^{18} eV (beyond the "knee" in the figure 2) remains a mystery.

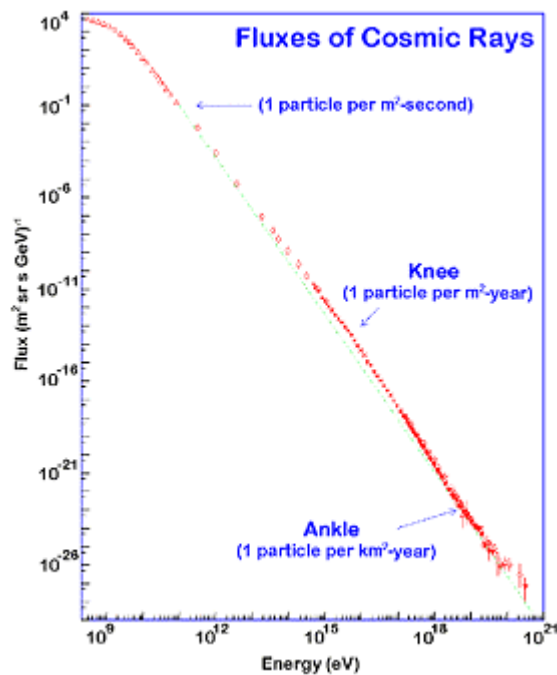


Figure 2: Energy Spectrum of Cosmic Rays

Detection and Measurement of Cosmic Radiation

The primary interests for cosmic ray scientists are the charge, energy and isotropic spectra for both galactic and solar cosmic radiation. The measurement of these spectra has proven to be a long and difficult effort and much still remains to be done. The difficulty in measurement lies in the wide range of charges and energies of cosmic rays. Also the numbers of the particles for each elemental type fall dramatically after hydrogen and helium and this makes detection even more difficult. In figure 3 we see that solar particles are rich in Hydrogen and Helium relative to galactic cosmic rays, probably due to selective acceleration mechanisms.

However, lithium, beryllium, and boron are more plentiful in galactic cosmic rays than in the Solar System.

There is no one instrument that can measure everything. In fact sometimes there is no instrument at all that can measure some of the data while the use of other instruments is prohibited due to the need to place the instrument outside the Earth's atmosphere in order to make the measurements. The Earth's atmosphere acts like a shield against the cosmic rays, it absorbs some cosmic rays, causes others to have collisions with the molecules making up the atmosphere and is partially invisible to other very small cosmic rays, some of which can travel right through the Earth. Some experiments conducted on the Earth's surface operate by detecting the sub-particles created in a collision between a cosmic ray and a molecule high up in the atmosphere (called a cosmic ray shower) and trying to decipher the original cosmic ray from the reconstruction of the collision. The highest energy ever attributed to a cosmic ray was detected using this method, [7]. The best place to measure the cosmic rays is outside the interference of the Earth's atmosphere. To put detectors in Space requires the help of space agencies like ESA and NASA. Satellites often carry instruments designed to measure features of the energy, charge, or isotropic spectra. Sometimes a complete satellite is dedicated to the measurement of cosmic rays and one such satellite was the Long Duration Exposure Facility, LDEF.

Long Duration Exposure Facility

LDEF was a specially designed satellite that was launched into low Earth orbit in 1984 and retrieved in 1990 having orbited the Earth some 3000 times, (see figure 4). LDEF contained fifty-seven individual experiments that made a wide array of measurements of galactic and solar cosmic radiation. A team of scientists headed by O'Sullivan and Thompson from the Dublin Institute for Advanced Studies designed the single largest experiment (UHCRE) on the LDEF. It covered one-fifth of the surface area of the LDEF and it was designed to measure the charge abundance of galactic cosmic rays with a charge greater than sixty, [8]. Previous attempts by prestigious research groups like Price et al. (Skylab) [9] and Binns et al. (HEAO satellite) [10] suffered from short duration exposures with small area collectors in their experiments which resulted in low statistics of cosmic rays for charges greater-than sixty. LDEF allowed for a long duration (six years) large area detector (10 meters squared) to collect primary cosmic rays without the interference of the atmosphere.

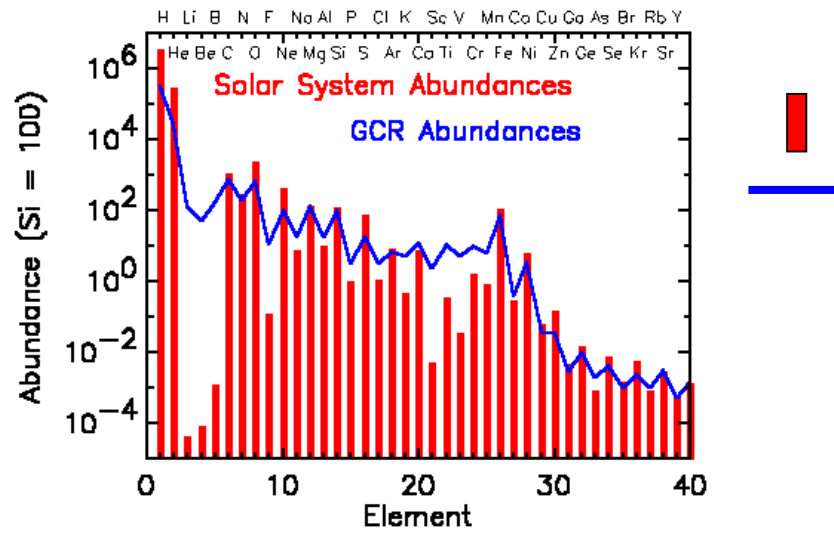


Figure 3: Abundance Spectrum of Cosmic Rays

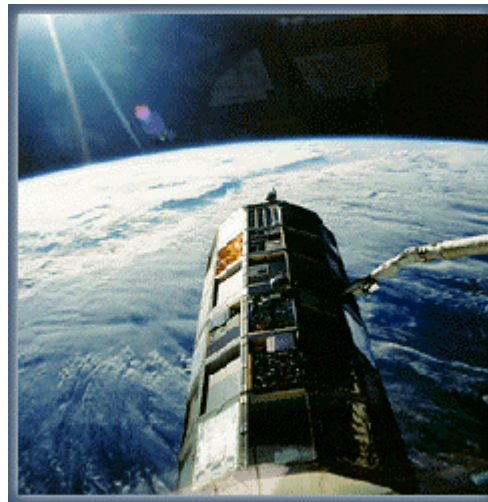


Figure 4: LDEF being deployed in Earth orbit by Shuttle *Challenger*

Data from over 3000 galactic cosmic rays with charge greater than sixty were collected by UHCRE. Among the UHCRE data was evidence of approximately thirty very rare cosmic rays called actinides (charges greater than 89). The total combined world sample of actinides previously detected was three so the UHCRE delivered ten times the world sample or a 1000% increase in data. UHCRE was the first experiment to measure sufficient quantities of ultra heavy cosmic rays that allowed for good statistical analysis to be carried out, (see figure 5), [11].

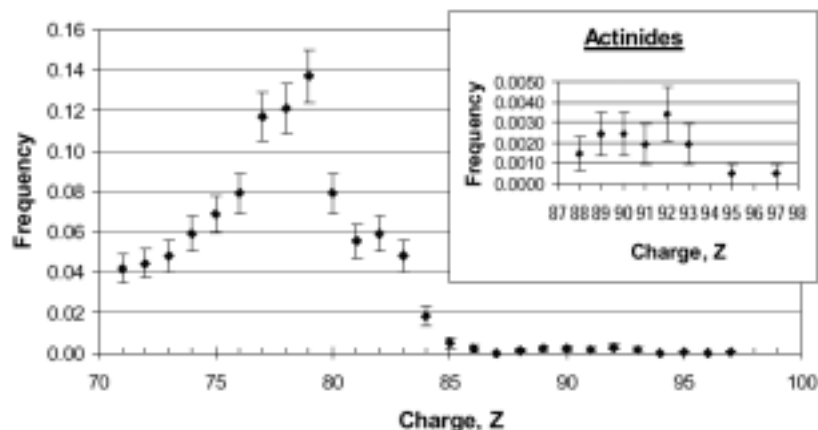


Figure 5: Charge frequency distribution of charges over 70 with an inset showing an enlargement of the histogram in the actinide region.

UHCRES detectors were made of a material called Lexan. This is a plastic type material that has some interesting properties. It was discovered in the 1960s that Lexan and other plastics recorded the passage of ionised particles and the trajectory of the particle could be enlarged using chemicals and viewed under a microscope, [12]. By careful controlled treatment of the plastics in the track enlargement process, (called track etching), parameters of the trajectory could be measured to give information leading to the identification of the energy and charge of an unknown particle. The sensitivity of Lexan was tested in various environmental conditions as a function of the charge and energy of known particles, [13]. This information was used to predict the response of the detector to any particle within the range of charge calibration, (see figure 6).

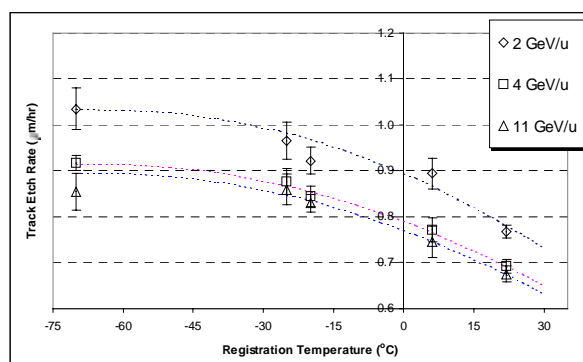


Figure 6: Registration temperature effect using relativistic gold at three different energies

Information from Cosmic Rays

Unfortunately cosmic ray trajectories do not point back to their sources so we must use indirect methods to determine their sources and the way they have propagated through the Galaxy. The chemical composition of the cosmic rays can provide a source for propagation

studies. The chemical composition of the solar system has been determined from a combination of spectroscopy on the Sun, studies of the solar wind, and by chemical analysis of meteorites, which are presumed to have a purer sample of the early solar system than terrestrial rocks, [14]. The composition of cosmic rays is important because cosmic rays are a direct sample of matter from outside the solar system and contain elements that are not seen in spectroscopic lines from other stars. Cosmic rays also provide important information on the chemical evolution of the Universe. If we look at the elemental composition measured for cosmic rays and compare it to our best understanding of the composition of the solar system, we quickly see some large differences. Information regarding the creation and existence of the elements can be found from the relative abundance of the cosmic rays. Some isotopes are radioactive so their existence or lack of it in cosmic ray samples can be used to estimate the age of the cosmic rays.

Some Final Comments

Just over one hundred years of investigation into cosmic rays has provided answers to many questions of phenomena observed on Earth, some examples being the discharging of electroscopes in laboratories and on a bigger scale, the cause of the *Aura Borealis* or otherwise known as the Northern lights. Many big questions still remain to be answered on the origin, composition, and propagation of cosmic rays. For reasons of simplicity and space in this article, I have completely ignored a whole area of cosmic ray research involving subatomic particles. These particles are much smaller than elemental nuclei and are often the result of collisions between other particles but are important for testing hypothesis of atomic models. This, as they say is another story. The investigation of elemental cosmic radiation has recently taken on a more important and somewhat urgent role to that of simple academic curiosity. It involves the conquest of Space. As we have noted already, outside the safety of the Earth's atmosphere is a constant 'rain' of charged particles that can easily penetrate many grams of thickness of lead. Astronauts and their spacecraft, as well as electronic equipment on satellites are vulnerable to long term exposure of cosmic rays and are particularly sensitive to high fluxes of charged particles like those that occur in solar flare events. The Earth's magnetic field can provide some protection from low energy particles for satellites in near-Earth orbit as long as the solar flare has the same magnetic polarity as the Earth's field. Periodically, a solar flare is ejected from the Sun with ionised gas in a magnetic cloud of opposite polarity to the Earth's magnetic field and this has resulted in wide spread blackouts in terrestrial power and communication systems. Research into early detection and measurement of the polarity of ionised gas clouds is taking place and this may result in satellites and power stations taking some form of action to minimise damage. Another

important question being asked today is whether astronauts would survive the high doses of radiation from a manned mission to Mars given the amount of cosmic radiation they would be exposed to during their extended journey time. Other research involves measuring the amount of cosmic radiation that is penetrating aircraft that fly at high altitudes, [15]. Our understanding of cosmic rays is proving to be vital for future expansion in communications and exploration of our Solar System.

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