Cosmic Rays

What are cosmic rays?

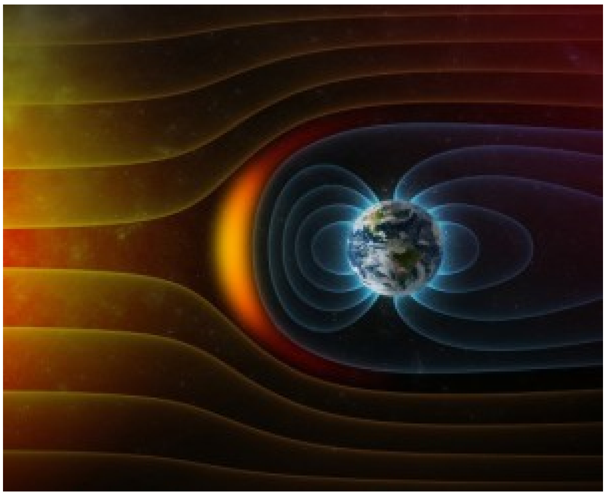

Geologists taking rock samples on James Ross Island for cosmogenic nuclide dating

Cosmic rays are high energy particles that flow into our solar system from outer space. They are essential for the production of ^{14}C in our atmosphere, which is used in radiocarbon dating, and in the production of cosmogenic nuclides in rocks at the Earth surface, which we use in cosmogenic nuclide dating[1-3].

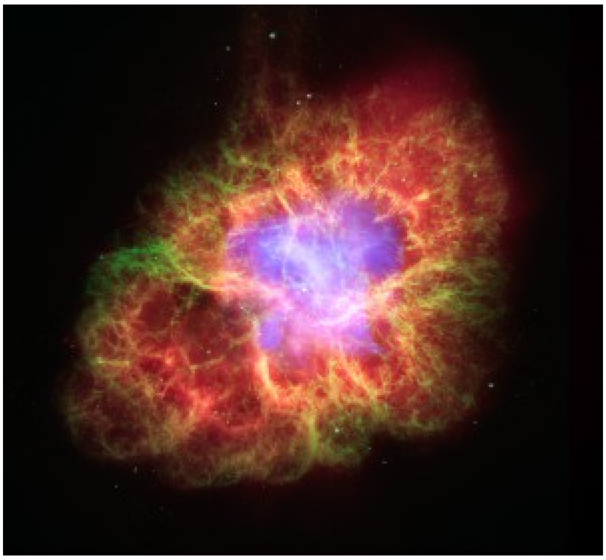
So, these rays are essential for many applications in Quaternary Science, but where do they come from?

Cosmic rays (also called cosmic radiation) mainly comprise high energy nucleons (protons, neutrons and atomic nuclei). About 90% are hydrogen nuclei (a single proton with an atomic number of 1). They have been stripped of their electrons and so are ionised.

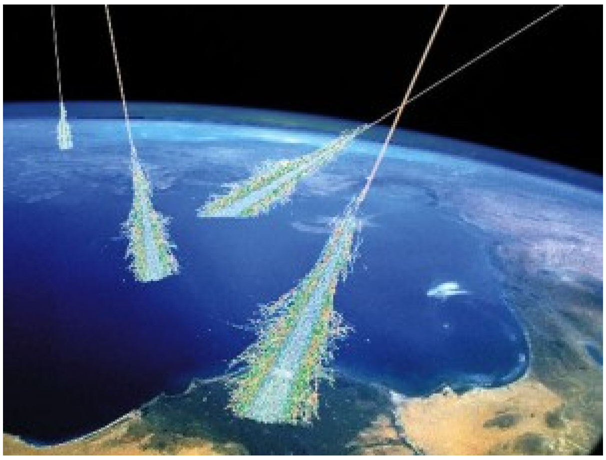
Cosmic rays pass through our galaxy at close to the speed of light. Their flight paths are uniform across the galaxy; they strike the Earth at random orientations.


Artist's impression of the way the Earth's magnetic field defends the planet from solar winds (from Shutterstock)

Cosmic rays are essentially normal matter that has been accelerated to near light speed by the shock waves produced from supernovae. The particles bounce about in the magnetic field of the remnant anomaly until they gain sufficient energy to escape the system, whereupon they become cosmic rays.


A supernova is a stellar explosion that briefly outshines an entire galaxy.

The cosmic ray cascade


The cosmic ray shower. It is now known that most cosmic rays are atomic nuclei. Most are hydrogen nuclei, some are helium nuclei, and the rest heavier elements. The relative abundance changes with

cosmic ray energy — the highest energy cosmic rays tend to be heavier nuclei. Although many of the low energy cosmic rays come from our Sun, the origins of the highest energy cosmic rays remains unknown and a topic of much research. This drawing illustrates air showers from very high energy cosmic rays. Image from NASA.

When cosmic rays collide with atoms in our atmosphere, they cause a cascade of reactions – we call this the 'cosmic ray cascade'.

The first interaction is when the high energy particles collide with nuclei in the upper atmosphere. They cause a 'spallation' reaction. A spallation reaction is a nuclear reaction where a highly energetic nucleon (usually a secondary cosmic-ray neutron of energy) collides with a target nucleus. This causes the release of multiple particles (protons, neutrons and clusters).

These particles cause a wave of secondary interactions and spallation reactions. The accelerated particles cause a cascade of interactions in the upper atmosphere as they strike more atmospheric nuclei, creating additional particles and high energy radiation. The particles continue in the same direction, while photons are emitted in all directions. Net energy is lost to the atmosphere.

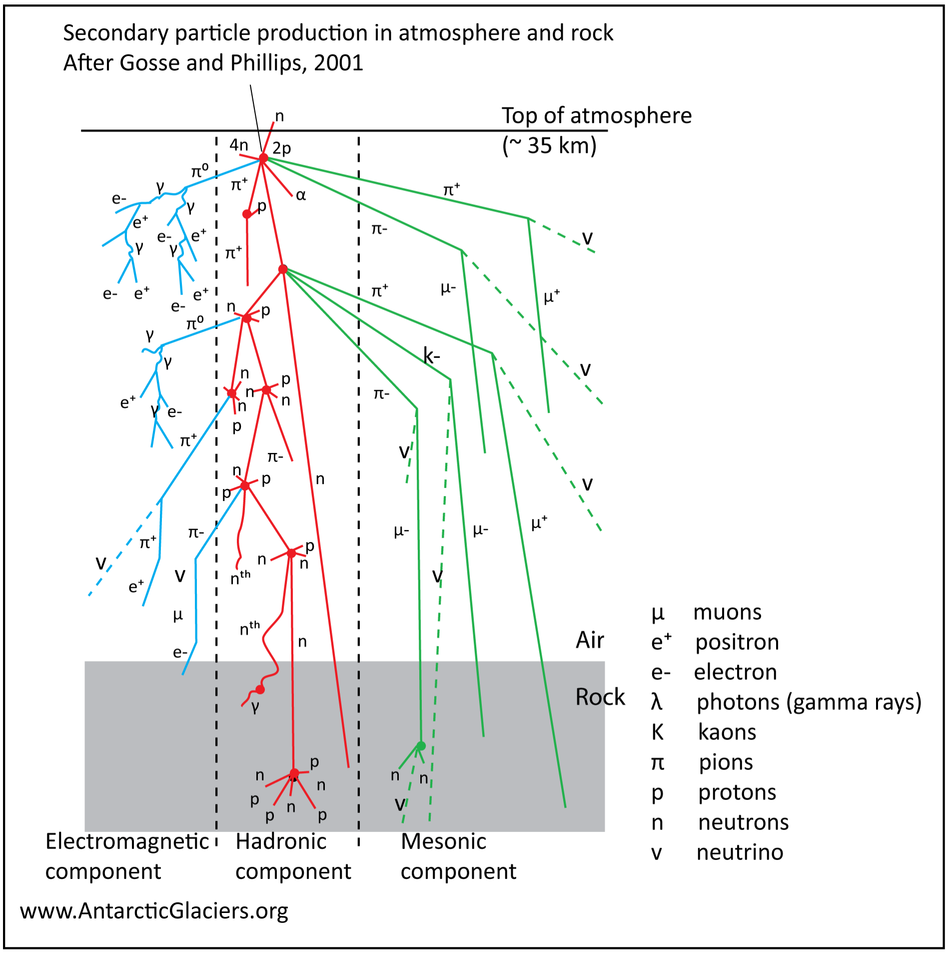
The cosmic ray cascade has essentially three components:

- The mesonic component
- The electromagnetic component.
- The hadronic component

The mesonic component consists of kaons (K) and pions (π) which degrade to muons (μ) (muons (mass 105.7 MeV/c^2), electrons (mass 0.511 MeV/c^2) and tau (mass 1777.8 MeV/c^2) are all leptons, which have no sub-structure and are not composed of simpler particles). A muon is about 2/3rds of the size of a proton or a neutron. They are unstable, lasting only a few hundredths of a microsecond.

The second part of the primary interaction is the electromagnetic component, where the muons undergo further decay. When the cosmic ray collides with an atom, the sub-atomic pions (π) and kaons (K) produced decay almost instantly to produce muons (μ) and photons (gamma rays) (γ). The muons and gamma rays then decay to form electrons (e^-) and positrons (e^+).

The hadronic component comprises protons (p) and neutrons (n). A hadron is a composite particle made up of quarks held together by a strong force. Hadrons comprise baryons (such as protons and neutrons) and mesons. Protons and neutrons are stable. This component of the cosmic ray cascade is most important for cosmogenic nuclide dating[4].



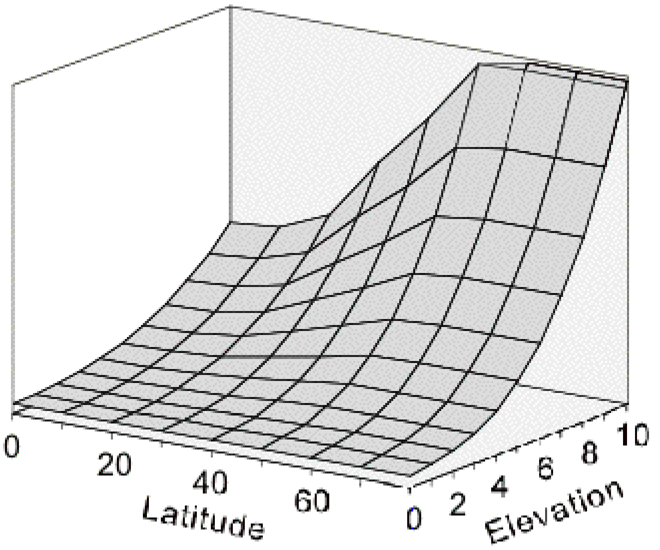
The cosmic ray cascade. Spallation reactions cause the formation of new cosmogenic nuclides in the atmosphere and in the lithosphere.

This ‘secondary radiation’ essentially has the same energy as the initial interaction. Through successive interactions, energy is lost until the particles have insufficient energy to cause a spallation reaction upon collision with another particle.

The cosmic ray intensity flux

The intensity at which cosmic rays collide with the Earth’s atmosphere varies. It varies with latitude, because the flux is modulated by the Earth’s magnetic field. As such, the cosmic ray flux at the equator is four times less than the flux at the poles. This is because cosmic rays are guided to the poles along the Earth’s magnetic field lines.

The cosmic ray intensity flux also varies with altitude. The secondary particle flux, formed after that first interaction, peaks at 15 km altitude.

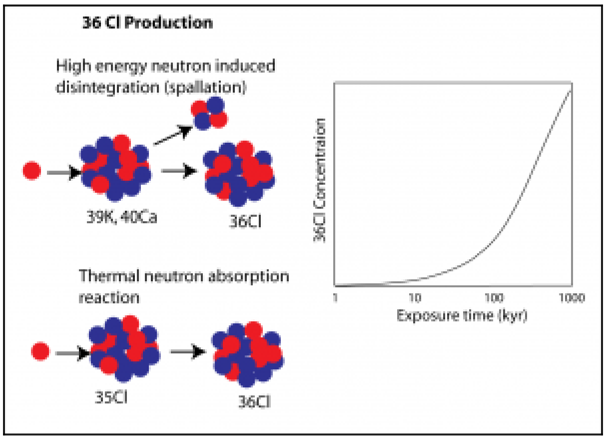


Variation of cosmic ray flux at the earth's surface as a function of altitude and latitude. From the [University of Glasgow Centre for Cosmogenic Nuclides]

It is therefore important to remember that both altitude and latitude effect the production rate of cosmogenic nuclides.

Formation of cosmogenic nuclides

As the cascade of reactions propagates down through the atmosphere, the nuclear particle flux becomes dominated by neutrons + minor mesonic flux. These secondary fast nucleons continue to produce cosmogenic nuclides in the atmosphere, hydrosphere & lithosphere by breaking apart target atoms through **spallation** interactions. Eventually, the particles have insufficient energy to cause spallation.



Cartoon illustrating the formation of Chlorine-36 through the process of spallation. The amount of cosmogenic nuclides increases over time.

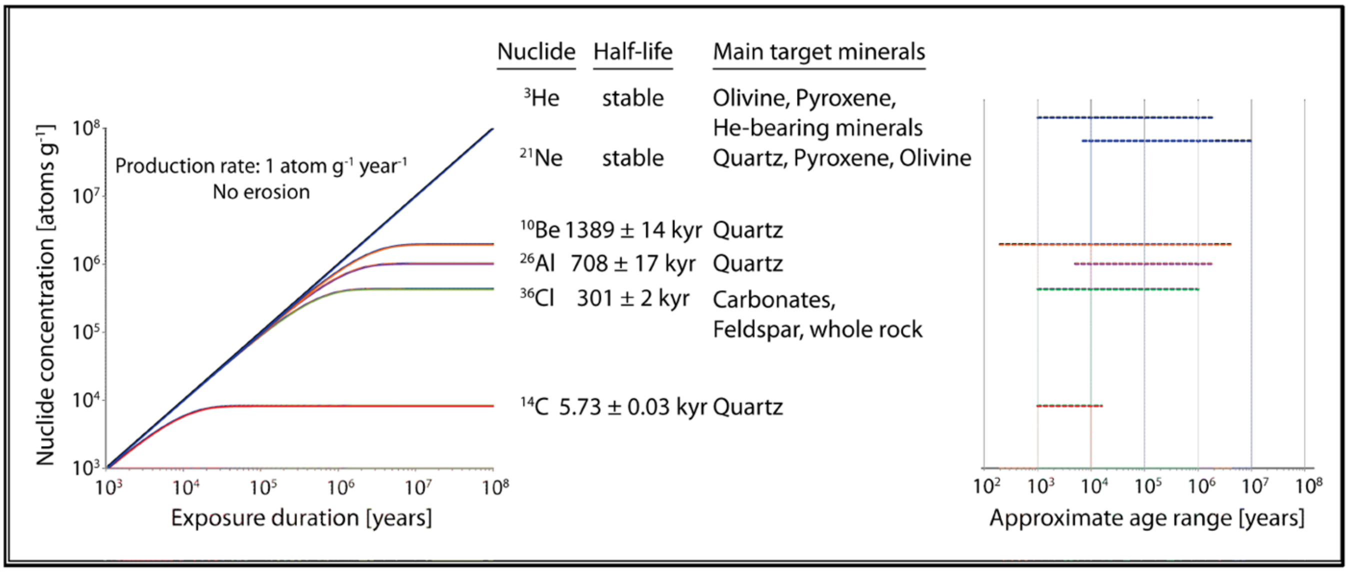
For cosmogenic nuclide dating, we are most interested in the cosmogenic nuclides formed *in situ* within rocks at the Earth's surface. The production of cosmogenic nuclides slows with depth in rock as the cosmic ray intensity flux becomes attenuated with depth[4]. Therefore, most cosmogenic nuclides are formed within the top few centimetres of a rock.

For cosmogenic nuclide dating, we are mostly interested in just six isotopes. These six particles do not occur naturally in the rock, have long-enough half-lives and high enough production rates to be useful, and there are no similar isotopes within the rocks to make measurement difficult.

The table below summaries the properties of these nuclides, and indicates in which minerals in rock they are formed, and from which atoms. From Ivyochs and Kober, 2007[5]. The nuclide chosen for analysis will depend on the target mineral available and the time range applicable (the expected exposure age for the rock).

Nuclide	Half-life	Other isotopes	Suitable minerals	Target elements	Production rate (atoms g^{-1} yr^{-1})	Applicable time range
^{10}Be	1.5 million years	^{9}Be	Quartz	Oxygen (O), Silicon (Si)	5	Several million years
^{14}C	5730 years	^{12}C, ^{13}C	Quartz	Oxygen (O)	16	Up to 20,000 years
^{26}Al	0.7 million years	^{27}Al	Quartz	Silicon (Si)	31	Up to several million years
^{36}Cl	0.3 million years	^{35}Cl, ^{37}Cl	All rock types	Ka, Ca, ^{35}Cl	10 (granite)20 (limestone)	Up to 1 million years
^{3}He	Stable	^{4}He	Olivine, pyroxene	Many	120	To millions of years
^{21}Ne	Stable	^{20}Ne, ^{22}Ne	Quartz, olivine, pyroxene	Si, Mg	20	10s of 1000s to millions of years

Eventually, boulders reach saturation, and radioactive decay limits further analysis. For exposure age dating (dating the time since the rock was exposed), the age range for cosmogenic nuclide dating therefore depends on the mineral chosen for analysis[1]. Beryillium-10 and Aluminium-26 (^{10}Be, ^{26}Al) are used most often because they are formed in quartz, which is widely available, and have long half-lives. Carbon-14 is formed in the atmosphere, and absorbed by living organisms. This principal is used in radiocarbon dating.



Properties of the six most common cosmogenic nuclides. From Darvill, 2013.

Further reading

For more information, see the pages about Cosmogenic Nuclide Dating in this section:

- Cosmogenic Nuclide Dating
- Quantifying ice-sheet thinning

Also see the excellent chapter on cosmogenic nuclide dating by Chris Darvill on the BSG website.

Good summary chapter on Surface exposure dating with cosmogenic nuclides by Ivyochs and Kober.

Glossary

Allochthonous	Rocks that have been transported & deposited (inc. erratics, alluvial fans, gelifluction, etc.
Attenuation length	Thickness of a material (rock, snow, ice) required to attenuate intensity of cosmic-ray flux due to scattering & energy absorption
Autochthonous	Rocks that have remained at or near site of formation
Cosmogenic nuclide	A nuclide formed during the process of spallation after the collision of an atomic particle and an energetic cosmic ray.
Galactic cosmic radiation	Energetic particles, mostly of protons, originating from outer space.
Inheritance	Retention of remnant cosmogenic nuclides from a previous exposure
Isotopes	Families of nuclides with the same atomic number
Kaon (k)	A K meson. Subatomic particle.
Muon (μ)	Subatomic particle made up of one quark and one antiquark. -ve muons: short-lived energetic lepton particles that decay quickly. Can penetrate rocks to depth.
Nuclide	Atomic species characterised by a unique number of atomic number and neuton number (e.g., ^{10}Be, which has 4 protons and 6 neutrons)
Pion (π)	Subatomic particle that degrades to a muon
Production rate	Rate at which a specific nuclide is produced from a specified element or in a mineral such as quartz. Varies spatially and temporally.
Spallation reaction	Nuclear reaction resulting from collision of a highly energetic secondary cosmic ray neutron of energy with a target nucleus.
Terrestrial cosmogenic nuclide	A nuclide produced by the interaction of secondary cosmic radiation with exposed target atoms in earth-surface materials.

References

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2. Balco, G., *Contributions and unrealized potential contributions of cosmogenic-nuclide exposure dating to glacier chronology, 1990-2010.* Quaternary Science Reviews, 2011. **30**(1-2): p. 3-27.
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