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COSMOGENIC RADIONUCLIDES IN ICE CORES

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Production of cosmogenic radionuclides
Cosmogenic radionuclides are produced continuously by cosmic rays penetrating from the space into the atmosphere. When cosmic ray particles impinge on the atmosphere they induce nuclear reactions producing secondary particles and a variety of new nuclides most of which are radioactive [1]. Depending on the energy of the primary particle a cascade develops through the atmosphere until all the secondary particles are used up in nuclear reactions or stopped by collisions and ionization processes. Since the main target elements of the atmosphere are nitrogen, oxygen, and argon most of the radionuclides produced have masses smaller than 40. In Table 1 some basic properties of the main cosmogenic radionuclides produced in the atmosphere are listed. The production rates are given as estimated mean global values. Some of the radionuclides, marked with an asterisk, are also produced artificially in considerable amounts by nuclear bomb tests, nuclear reactors, and accelerator facilities.

Isotope	Target	Half-Life	Prod. Rate (atoms cm^{-2} s^{-1})	Inventory
^{3}H*	N, O	12.3 y	0.2	3 kg
^{7}Be	N, O	53.4 d	0.04	20 g
^{10}Be	N, O	1.5 10^{6} y	0.02	100 tons
^{14}C*	N	5730 y	2	60 tons
^{26}Al	Ar	7.3 10^{5} y	0.0002	1 ton
^{32}Si	Ar	150 y	0.0004	1 kg
^{36}Cl*	Ar	3 10^{5} y	0.001	4 tons
^{129}I*	Xe	1.6 10^{7} y	0.00003	20 tons

Table 1: Cosmogenic radionuclides which are produced in the atmosphere [1]. Asterisks indicate radionuclides which are also produced artificially. In addition ^{129}I is a natural product of the spontaneous fission of uranium. The global inventory is based on the present production rate.

Transport and deposition of cosmogenic radionuclides
As a consequence of the nuclear interaction of the galactic cosmic rays with the atmosphere and the shielding effect of the geomagnetic field the production rate of the cosmogenic radionuclides depends mainly on altitude and latitude (Fig. 1). After production the radionuclides are subject to different processes according to their geochemical properties. For example ^{14}C is oxidized to $^{14}CO_2$ and ^{10}Be becomes attached to aerosols. Since the

stratosphere is thermally stratified and separated from the troposphere by the tropopause, the mean residence time for aerosols in the stratosphere is about 1-2 years. In the troposphere precipitation removes most atmospheric constituents within a few weeks.

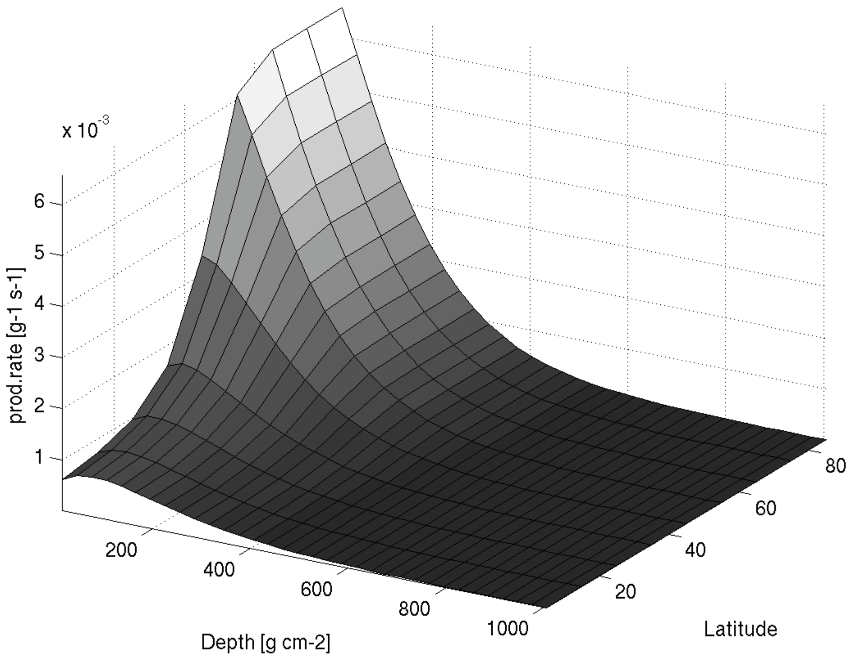

Fig. 1: Dependence of the ^{10}Be production rate on atmospheric depth (0: top of atmosphere; 1033: sea level) and latitude for the present geomagnetic field intensity and the solar modulation [1].

Detection of cosmogenic radionuclides

As shown in table 1 cosmogenic radionuclides are very rare resulting in very low isotopic ratios (10^{-10} - 10^{-14}). Such low ratios cannot be determined by conventional mass spectrometry due to background problems. In most samples isobars and molecules with the same mass are present in much higher concentrations which leads to serious interferences with the radioisotope to be analyzed.

One way to detect cosmogenic radionuclides is to make use of their radioactive decay. This technique is straightforward and works well as long as the half-life is short (<1000 y). However, for longer half-lives decay counting becomes inefficient. Conventional mass spectrometry is not sensitive enough to measure such extremely small isotopic ratios. Going to much higher energies by using accelerator mass spectrometry (AMS) provides the key. This technique is able to detect as few as a million atoms [2].

Archive ice

Some of the cosmogenic radionuclides are deposited in natural archives were they are stored for thousands of years preserving information about their production and transport history. Beside sediments and tree rings (^{14}C) ice cores proved to be excellent archives because they directly sample all the fallout from the atmosphere. Polar ice sheets are formed from snow. The snowflakes grow together to grains which slowly increase in size. Due to the pressure of

the overlying new snow layers, the grains become more and more compacted and finally turn into ice.

A special property of ice is that it slowly flows towards the margin of the ice sheet, where it partly melts and partly breaks up as icebergs. As a consequence of the horizontal movement of the ice, the annual layers become thinner with increasing depth leading to a non-linear relationship between depth and age. This has the advantage that the recent past can be studied in detail whereas the far past is still covered, though with low resolution. The disadvantage however, is that dating of ice cores is difficult.

Cosmogenic radionuclides and solar variability

The production and transport of cosmogenic radionuclides in the atmosphere are shown schematically in Fig. 2. These processes are influenced by several factors.

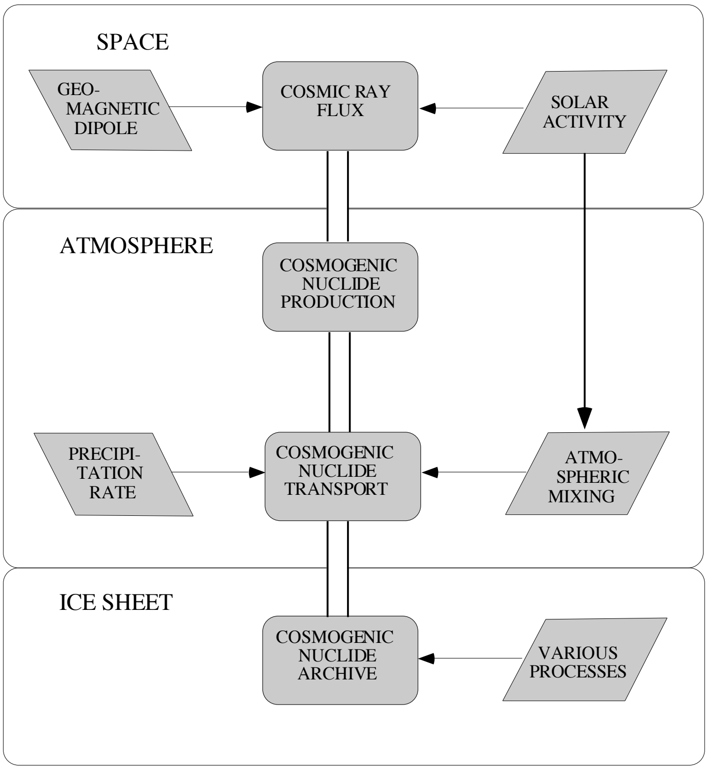

Fig. 2: Schematic diagram of production, transport, and storage of cosmogenic radionuclides in an ice sheet. These processes are influenced by several factors such as solar activity, geomagnetic field intensity, atmospheric mixing, precipitation rate and various processes within the ice sheet.

Within the solar system there are two effects caused by the Sun and the Earth giving rise to fluctuations in the cosmic ray flux. Both are due to magnetic shielding effects on the charged cosmic ray particles.

The first is related to the solar activity. The sun emits solar wind from coronal holes that carries "frozen-in" magnetic fields. The emission of solar wind leads to significant fluctuations of the cosmic ray flux. The most prominent feature is the 11-year Schwabe cycle. But there are also longer periodicities (e.g. 88 year Gleissberg cycle, 205 year Suess cycle)

and decadal periods of low solar activity such as the Maunder minimum (1645-1715 AD). The heliomagnetic shielding affects primarily the particles with low energies. Reconstruction of solar activity became an especially important issue because direct measurements of solar irradiance (solar constant) with satellite-based radiometers revealed variations in phase with the 11-year Schwabe cycle over the last two decades [3]. The yearly averaged amplitude of this cycle is too small (0.1%) and the changes are too fast to induce relevant climatic changes. However, this does not mean that over longer time scales, the solar irradiance did not undergo much larger changes, which may have significantly affected the climate [4]. In fact, there are clear indications that solar forcing has controlled the drift of sea ice in the North Atlantic during the Holocene [5].

The second modulation effect is related to the geomagnetic dipole moment. From the analysis of the magnetic remanence measured in sediments and volcanic rocks it is known that the Earth's dipole field changes continuously and sometimes even reverses its polarity. The geomagnetic dipole field has a shielding effect on the intensity of low-energetic particles penetrating into the atmosphere. This effect is largest at low latitudes and disappears at the poles leading to a latitude-dependent production rate (Fig. 1). The production rate of cosmogenic radionuclides is especially sensitive to periods of low geomagnetic field intensities such as the Laschamp and the Mono Lake event 40'000 and 30'000 years before present [6].

The transport and the deposition are affected by atmospheric mixing processes such as the exchange between stratosphere and troposphere and the precipitation rate. Hence, at a specific site, the fallout of a cosmogenic isotope bound to aerosols depends very much on the local precipitation rate. The more it rains the more radionuclides are removed and the concentration is rather constant. If however, as during glacial periods, the mean global temperature drops and the water cycle is reduced on a large scale, then less water removes the same amount of cosmogenic radionuclides leading to higher concentrations [7]. In regions with low precipitation rates (deserts, Antarctica) dry deposition has also to be taken into account.

Finally even after deposition on an ice sheet some processes can occur. As an example, measurements of ^{36}Cl show that depending on the accumulation rate and the acidity of the snow, some of the ^{36}Cl may form $H^{36}Cl$ and escape from the ice back into the atmosphere [8].

In conclusion, measuring cosmogenic radionuclides in ice cores provides a wealth of information on cosmic rays, solar activity, geomagnetism, and atmospheric transport and deposition processes. Separation of the different components can be achieved by combining different radionuclides from different sites.

References

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