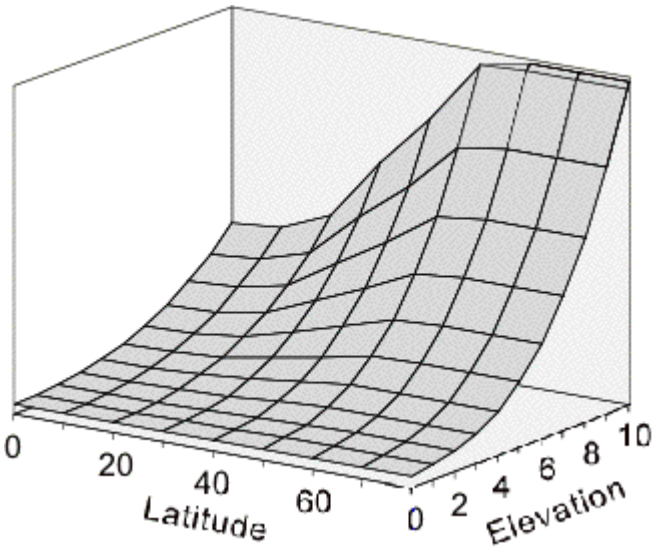
Cosmogenic nuclide scaling scheme

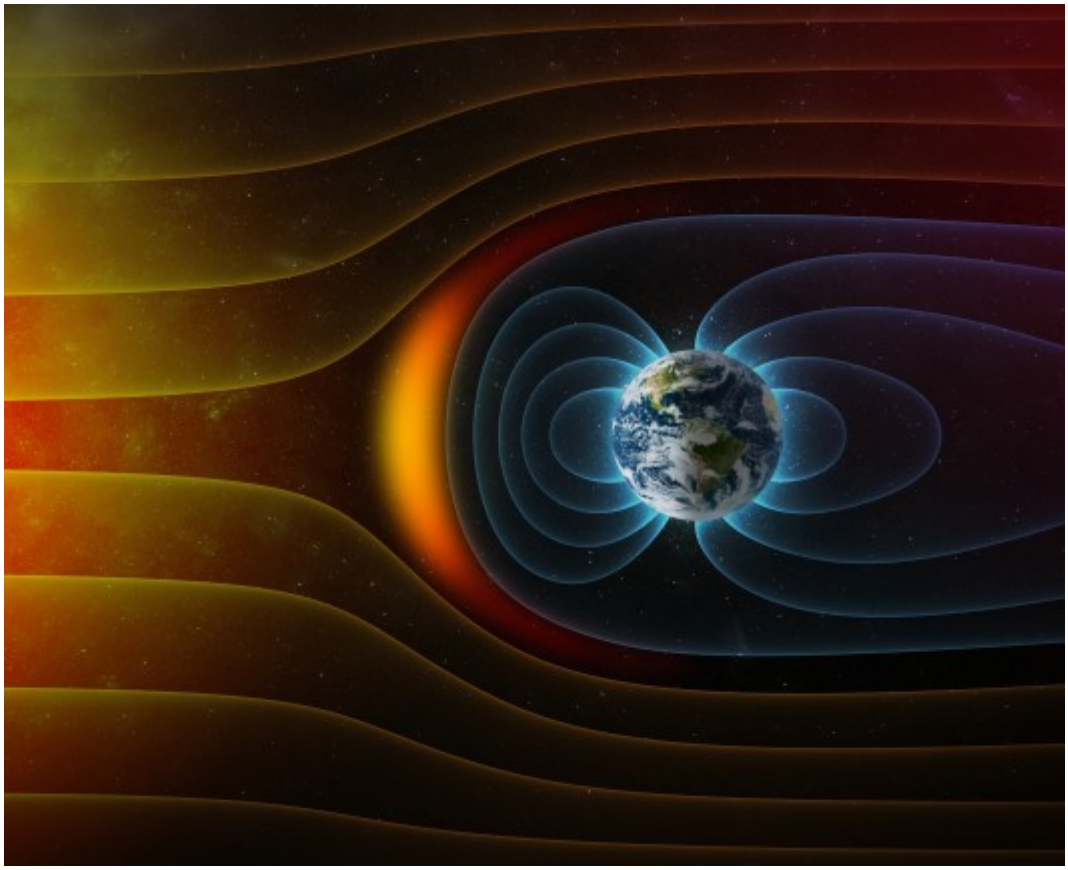
Influence of Earth's magnetic field and solar activity

The primary cosmic rays approaching Earth are affected by the Earth's magnetic field and solar activity (Darvill, 2013), with most rays penetrating the atmosphere at the poles and least at the equator. The ability of a ray to penetrate the atmosphere is determined by the angle of incidence and their location relative to geomagnetic field lines.

Variations in the Earth's magnetic field cause variations in the long-term primary ray production, and affect the flux of cosmic radiation at the Earth's surface. The regional or global production rate must therefore be scaled for **latitude and altitude** to create an estimate of the site-specific production rate. These scaling schemes take into account altitude and latitude (Dunai, 2001; Stone, 2000), variations in geomagnetic field strength, changes in solar activity (Lifton et al., 2008), and temporal changes in the energy spectrum (Lifton et al., 2014).



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



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

There are six primary scaling schemes commonly used (Table 4). At latitudes greater than 30° and elevations below 3000 m, there is little difference between the scaling schemes (Dunai and Lifton, 2014). However, differences of up to 30% may arise between models at lower latitudes and higher elevations. Users should ensure consistency when comparing ages between different studies that may have used different production rates and scaling factors (Balco, 2011; Darvill, 2013).

Particle transport models

Neutron-monitor based models (De, Du) are prone to overestimate the altitude dependence of cosmogenic- nuclide production (Martin et al., 2017). The LSDn scaling scheme (Lifton-Sato-Dunai) is a newer, more complex scaling scheme based on particle transport models (Lifton et al., 2014), and is recommended by Borchers et al. (2016). It provides information available neither from the traditional Lal (St) scaling scheme, or the neutron-monitor based scaling schemes (Du, Li, De) (Marrero et al., 2016a).

LSDn also provides a separate scaling factor for each nuclide, rather than a single scaling factor for all nuclides (*ibid*). LSDn has a good agreement with the older Lal-Stone model (Martin et al., 2017).

Scaling schemes

The production rate therefore changes, or is scaled, through time, according to the scaling scheme used and the sample’s latitude, longitude and elevation (Balco et al., 2008). Time-independent scaling schemes (St) result in a constant production rate.

Scaling scheme abbreviation	References	Time dependency (constant or variable production rate)	Description
St (Lal/Stone)	Lal (1991); Stone (2000)	Time-independent (constant production rate)	Altitude, latitude taken into account. Does not take into account magnetic field variations.
Lm ('Lal modified')	Lal (1991); Nishiizumi et al., (1989); Stone (2000)	Time-dependent (variable production rate)	Time-dependent version of St, based on time-variation in the dipole magnetic field intensity. Production rates vary with time according to magnetic field changes.
De (Desilets)	Desilets et al. (2006)	Time-dependent	Based on neutron monitor measurements and incorporating dipole and non-dipole magnetic field measurements. Production rates vary with time according to magnetic field changes.
Du (Dunai)	Dunai (2001)	Time-dependent	Based on neutron monitor measurements and incorporating dipole and non-dipole magnetic field measurements. Production rates vary with time according to magnetic field changes
Li (Lifton)	Lifton et al. (2005)	Time-dependent	Based on neutron monitor assessments and incorporates dipole and non-dipole magnetic field fluctuations and solar modulation. Production rates vary with time according to magnetic field changes and changes in solar output.
LSDn (Sf, Sa) (Lifton-Sato-Dunai)	Lifton et al. (2014)	Time-dependent	Based on equations from nuclear physics model. Incorporates dipole and non-dipole magnetic field fluctuations and solar modulation.

Table 4. Scaling schemes for cosmogenic nuclide production. Numerous sources (Balco et al., 2008; Dunai and Lifton, 2014; Marrero et al., 2016a).

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