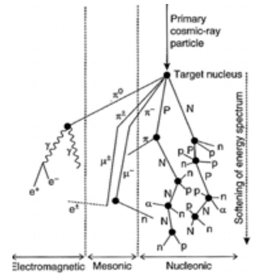
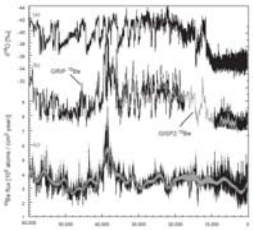


Lecture 10



Cosmogenic Isotopes I:

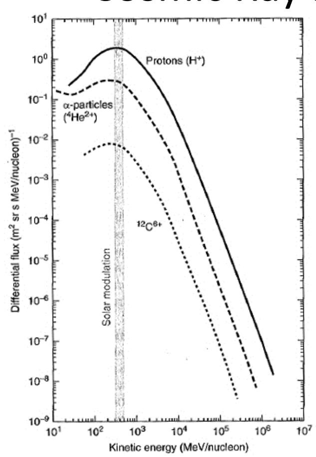
Production, Mechanisms, Applications

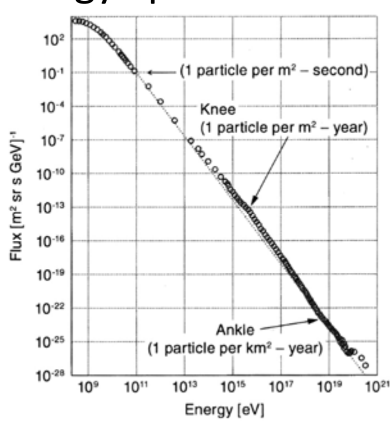
Beer, J., K. McCracken, and R. von Steiger (2012) "Cosmogenic Radionuclides" *Springer-Verlag* (Berlin) 426 pp

Cosmic Rays

- High energies largely produced by supernovae
  - Accelerated by shock waves to extremely high energies (>> 1 GeV, i.e., >> nuclear B.E.)
  - Mostly from our own galaxy, with SN every 30-50 y
- Lower energies locally (heliosphere) produced
  - Typically < 50 MeV
- Charged particles (largely protons, some alphas)
  - Bent by stellar, interstellar magnetic fields
    - Mean interstellar fields ~10^{-10} T (10^{-6} G)
    - Net effect: gyration radius ~ 10^{-4} pc ~ 20 AU
    - Cosmic rays don't "advect", they "diffuse" through space

Cosmic Ray Energy Spectra

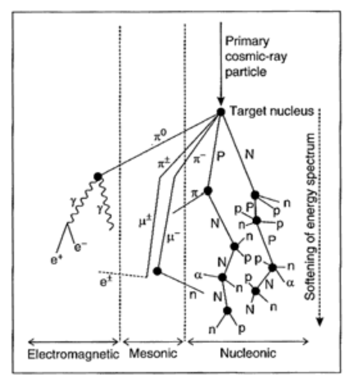




Spectrum is ~ $E^{-2.4}$

What we see at sea level…

- Mostly secondaries



Thermal neutrons drive n-capture, are isotropic

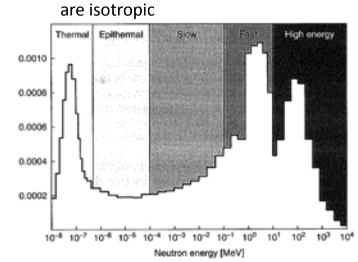
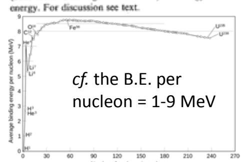
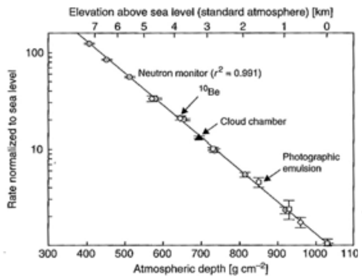


Fig. 1.3. The energy spectrum of secondary cosmic ray neutrons at sea level (data from Goldhagen *et al.* 2002). Lethargy is the natural logarithm of energy. For discussion see text.



cf. the B.E. per nucleon = 1-9 MeV

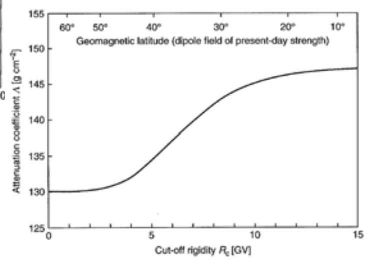
Attenuation is altitude, latitude, and energy dependent



"Rigidity" = pc/q

Related to gyroradius

(p = momentum ~ $KE^{1/2}$)



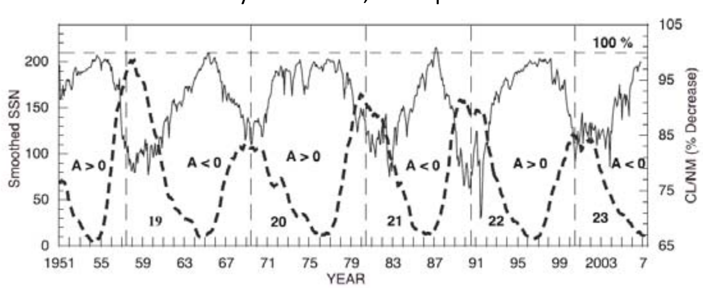
Higher flux at higher altitudes and higher latitudes

Factors Affecting Flux to Earth

- Local Interstellar Environment
  - Earth moves into/out of "Local Stellar Environments" every few 100 Ka, and into/out of galactic spiral arm every 70 Ma
- Solar activity
  - Affects local geomagnetic fields & heliosphere
  - Sunspot/Hale cycle
- Geomagnetic field
  - Longer term geodynamo wobbles (VADM)

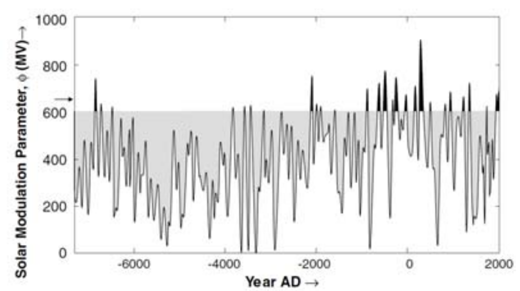
Solar (short term) Modulation

- Hale (22 year) and Schwab (11 year) cycles
  - NB: shape difference by solar magnetic phase
    - Influenced by solar sheaf, heliospheric modulation



Solar (long term) Modulation

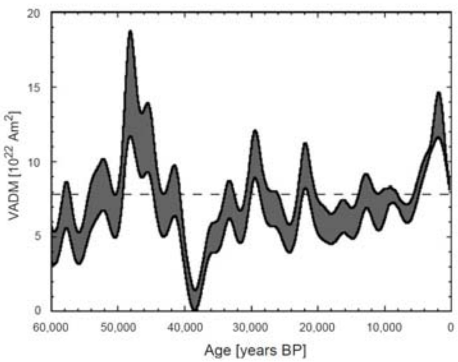
- Grand solar minima in sunspot numbers (e.g. Maunder Minimum)



Even longer term variations due to Geodynamo changes

Factor of two variations in magnetic field strength (VADM) over last 60 Ka

- Obtained from magnetic records in sediments and from ^{10}Be & ^{36}Cl records in ice cores

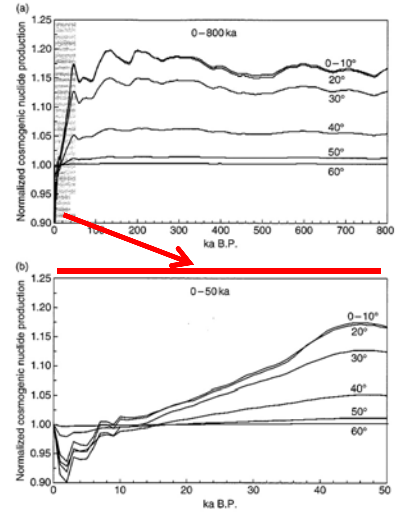


Muscheler, R., J. Beer, P. Kubik, and H. A. Synal (2005), Geomagnetic field intensity during the last 60,000 years based on ^{10}Be and ^{36}Cl from Summit ice cores and ^{14}C, *Quaternary Science Reviews*, *24*, 1849-1860.

Changes in flux over last 800 Ka

Significant changes over last 50-60 Ka

- Earth's movement into new "Local Stellar Environment"
- Especially since the Holocene
- Implications for paleo-cosmogenic records

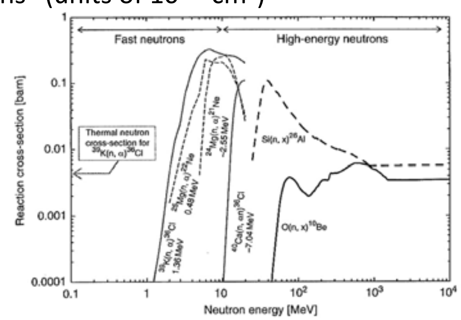


Cosmogenic Production Mechanisms

- Atmospheric
  - Spallation (nuclear billiards)
    - Very high energy, > nuclear B.E.
    - n, p on ^{14}N & ^{16}O → ^{3}He, ^{7}Be, ^{10}Be
    - n,p on ^{40}Ar → ^{26}Al, ^{36}Cl
  - Neutron capture/displacement
    - $^{14}N(n,p)^{14}C$
- Lithospheric and Cryospheric Also
  - Some spallation, but also n-capture, n-α

Reaction Cross Sections (probabilities)

- Depend on energy in a complicated way
- Depend on particle and nuclear wave functions
- A cross-sectional (geometric) area measured in "barns" (units of 10^{-24} cm^2)
- e.g.,

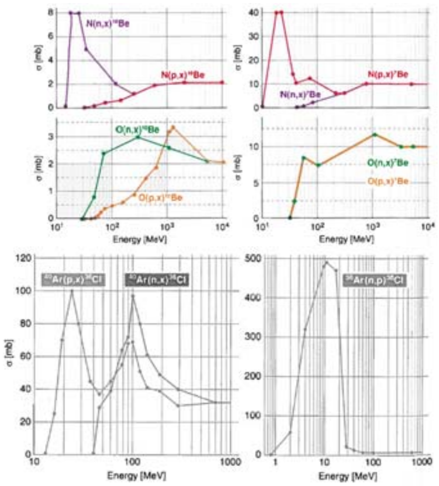


Cross sections for nuclear reactions

Strong resonances as well as function of E

Inter-related with atmospheric abundances as well

E.g., ^{40}Ar and ^{36}Ar (latter is 0.3% of former)yet very high σ at low E



Cosmogenic Atmospheric Production Rates

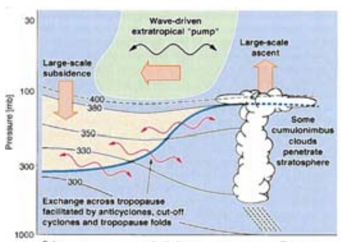
Nuclide	Half-life (years)	Prod Rate (atoms $cm^{-2}s^{-1}$)	Global Activity (Bequerels)	Global Inventory (g)
^{3}H	12.34	0.26		
^{7}Be	0.146	0.040		
^{10}Be	$1.4x10^{6}$	0.021		
^{14}C	5730	2.02		
^{26}Al	$7.2x10^{5}$	$4.7x10^{-5}$		
^{36}Cl	$3.0x10^{5}$	$1.1x10^{-4}$		
^{129}I	$1.6x10^{7}$	$4.2x10^{-6}$		

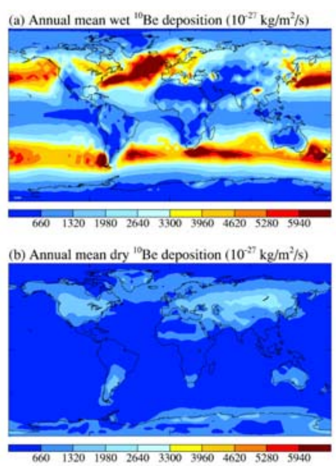
NB: Surface area of the earth = cm^2

Atmospheric Cosmogenic Production

Cosray attenuation ~ 100-150 g-cm

- Atmosphere is ~1000 g cm^{-2}
  - Thus attenuation is ~e^{-7} ~ 0.001 at sealevel
  - Most production high in atmosphere
- Residence time in stratosphere a few years
  - Best connection to troposphere at mid to high latitudes
- Slow inter-hemispheric (N-S) exchange





^{10}Be

1. Supplied to ice (archives) by combination of wet (dominant) and dry deposition
2. There is a modest (2-3%) contribution from *in situ* cos-ray production
3. Chronology in ice cores derived from (annual) layer counting and externally dated volcanic ash layers

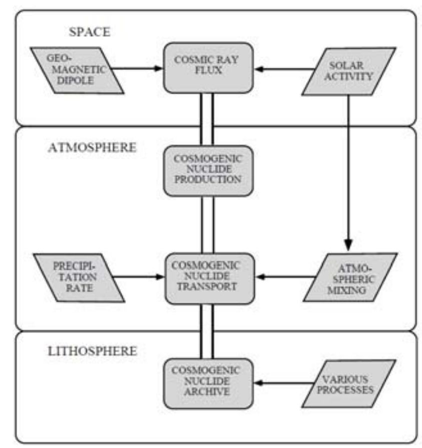
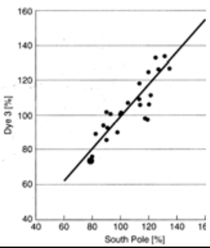
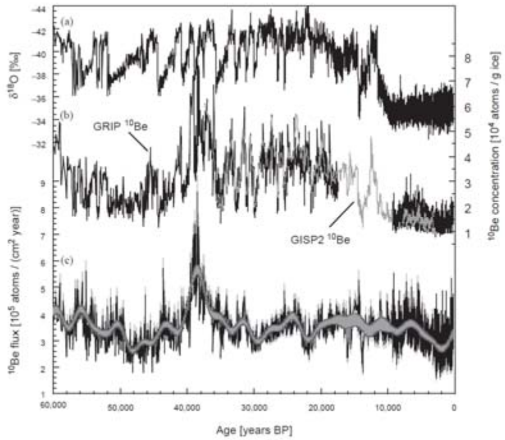


Fig. 2. Schematic overview of the production of ^{10}Be and ^{36}Cl and the processes influencing their concentration found in an archive such as a polar ice sheet.

^{10}Be records from polar ice cores

^{10}Be ice record is a proxy for both paleomag and cosmogenic production rates





Lithospheric Cosmogenic Nuclide Applications

- There is surface-intensified production of stable and radioactive nuclides in rocks (^{3}He, ^{10}Be, ^{21}Ne, ^{26}Al, ^{36}Cl, ^{39}Ar) that naturally have low background
- Combination of fast neutrons (~150 g-cm) and more penetrating muons (>1000 g-cm)
- Can be used to determine exposure ages and erosion rates
  - E.g., for steady erosion ε and constant production *P* rates:

$$N(x,t) = N(x,0)e^{-\lambda t} + \frac{P(0)}{\lambda + \mu\varepsilon} e^{-\mu x}\left(1 - e^{-(\lambda+\mu\varepsilon)t}\right)$$

  - Where μ is attenuation scale length, λ is half-life
  - Challenges:
    - Changes in erosion & production rates over history of surface
    - Shielding (local geography/geometry)
    - Coverage (lichen, snow, dust/soil) & changes

Lal, D., 1991. Cosmic ray labeling of erosion surfaces: *in situ* nuclide production rates and erosion models. Earth and Planetary Science Letters 104, 424-439.

A useful Excel add-in for cosmogenic nuclide applications: “cosmocalc” on 12.744 web site and also at http://cosmocalc.googlepages.com