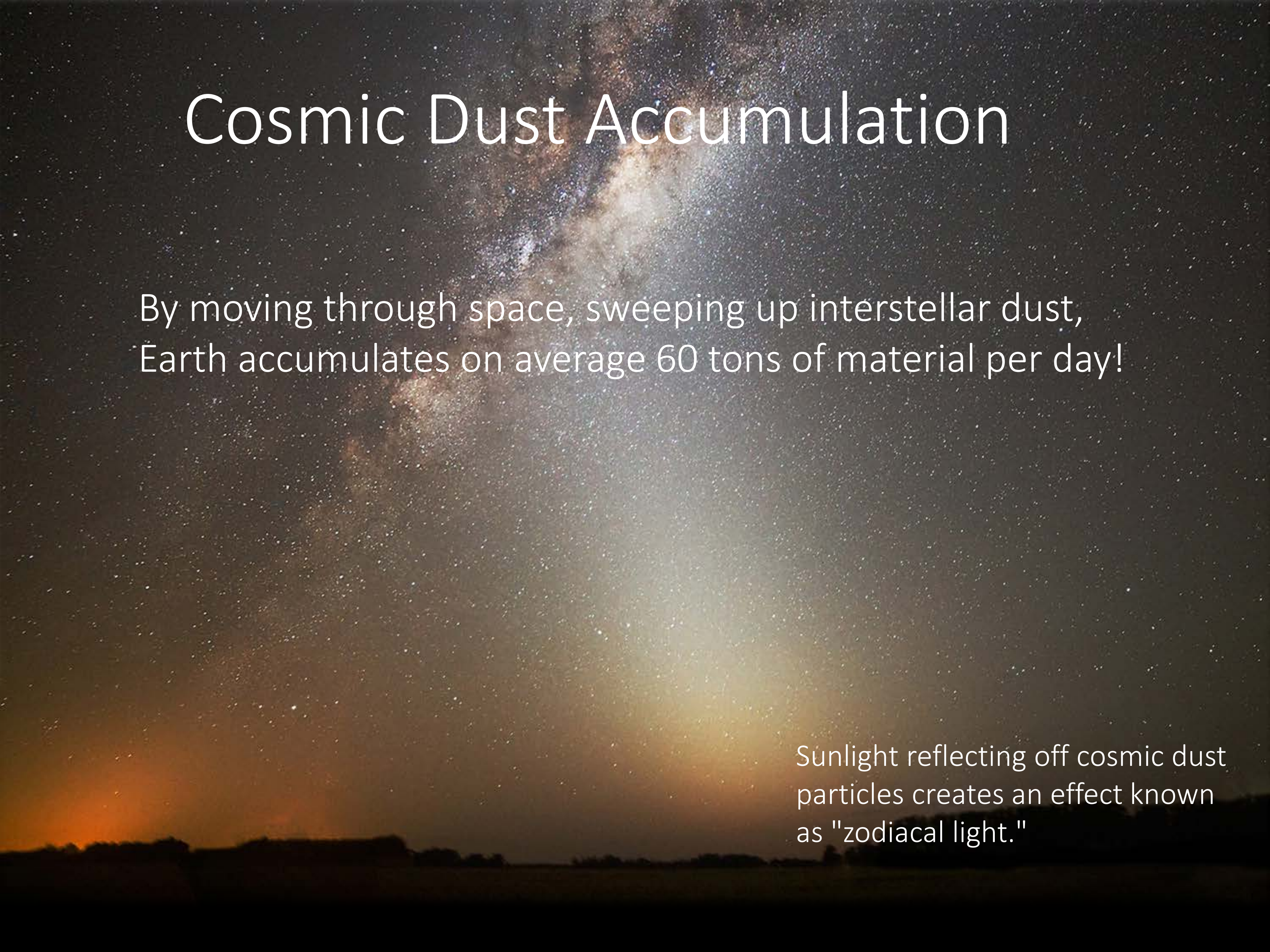
Radioactivity

Lecture 13

Radioactivity in the Atmosphere

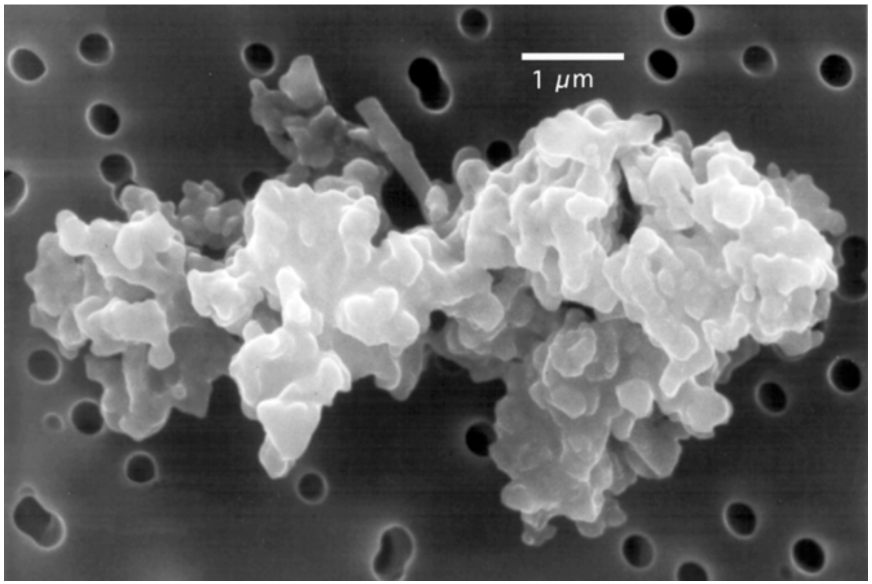
Cosmic Dust Accumulation

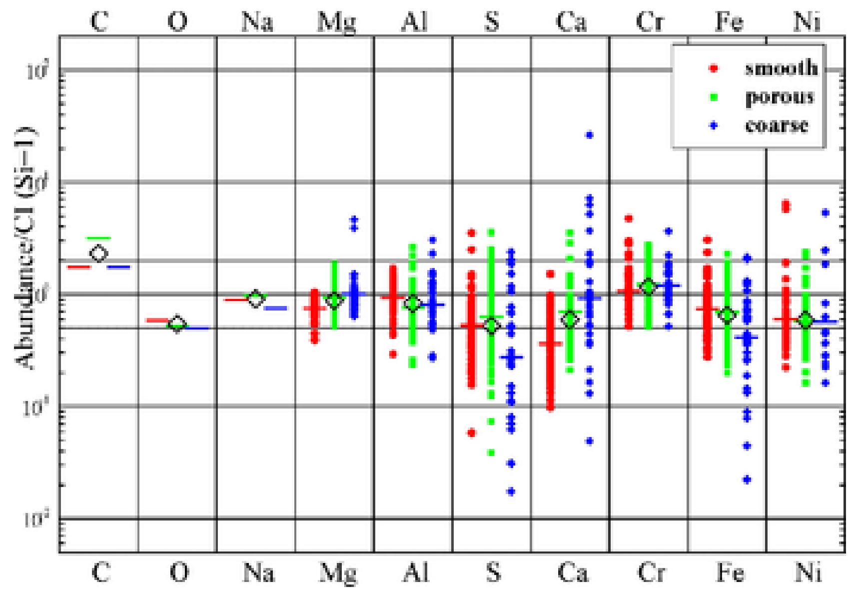
By moving through space, sweeping up interstellar dust, Earth accumulates on average 60 tons of material per day!



Sunlight reflecting off cosmic dust particles creates an effect known as "zodiacal light."

Dust composition and radioactivity





	U abundance (ppm)
Meteorites	0.008
Primitive mantle	0.021
Continental crust	1.4

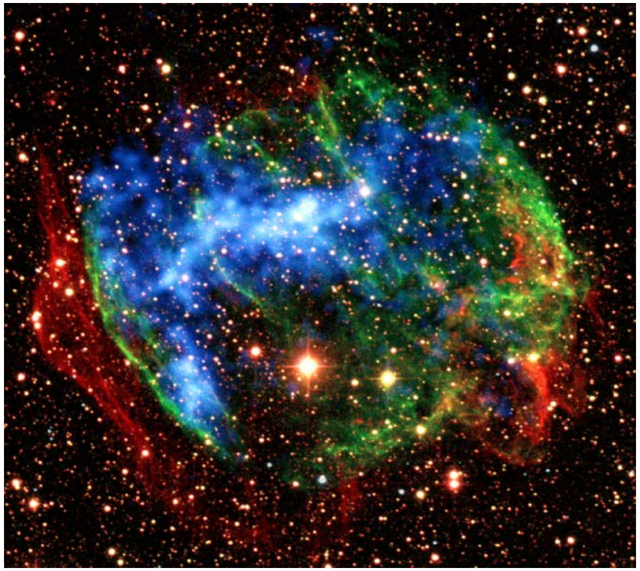
$$with\ 60\ tons\ of\ meteoritic\ dust\ daily: M(^{238}U) \approx 1g/day$$

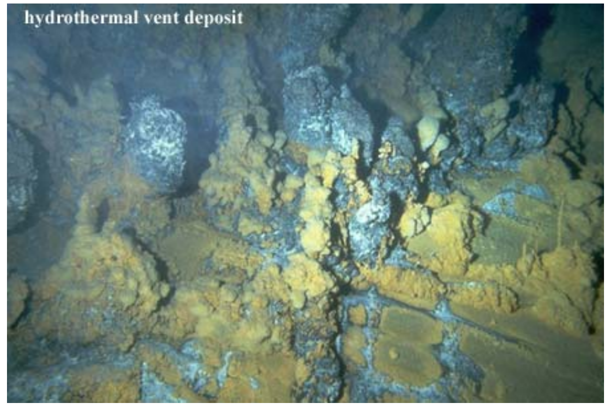
$$N(^{238}U) = \frac{6.022\cdot 10^{23}}{238g}\cdot 1g = 2.54\cdot 10^{21}\ part/day$$

$$A(^{238}U) = \frac{\ln 2}{4.5\cdot 10^{9}\cdot 3.14\cdot 10^{7}\,s}\cdot 2.54\cdot 10^{21}\ part/day$$

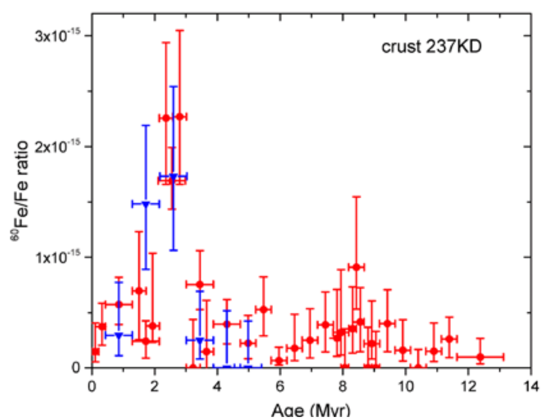
$$A(^{238}U) = 12460\ Bq/day$$

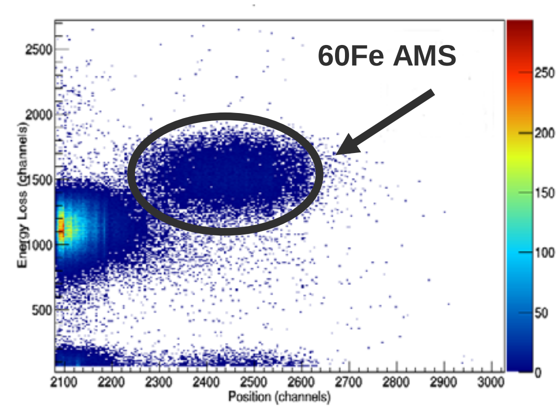
Except for 2.5-3.0 Ma ago ...

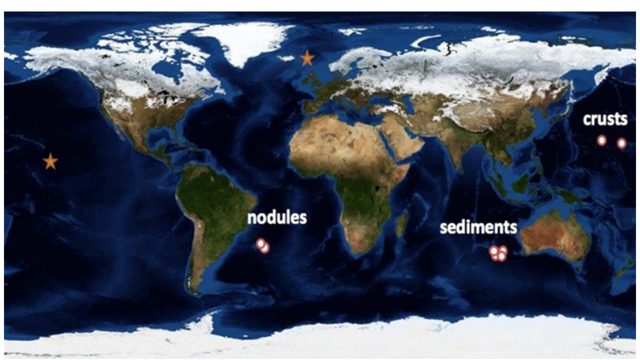




The radioactive isotope, ^{60}Fe is ejected into the Universe through supernova explosions. Trace amounts of ^{60}Fe has been discovered on the moon and in Earth's ocean crust, dating back to several millions of years ago.





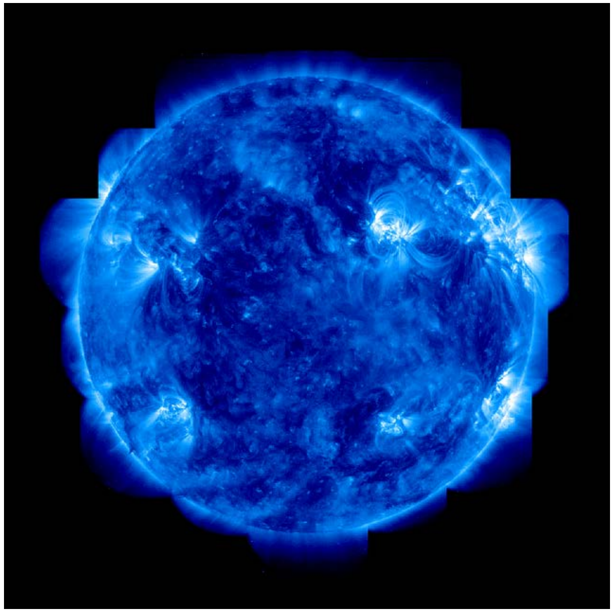


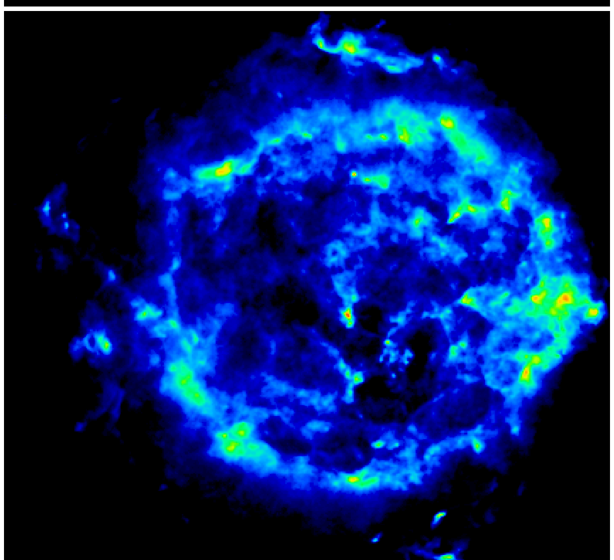
Earth was showered with radioactive dust between two and three million years ago! Extinction or developmental boost?

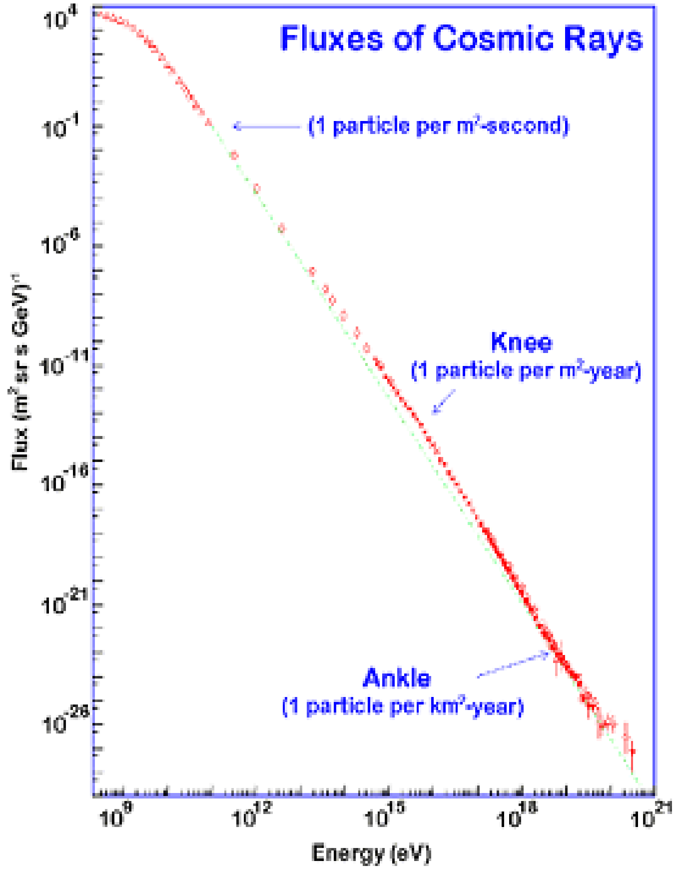
Cosmogenic Radioactivity

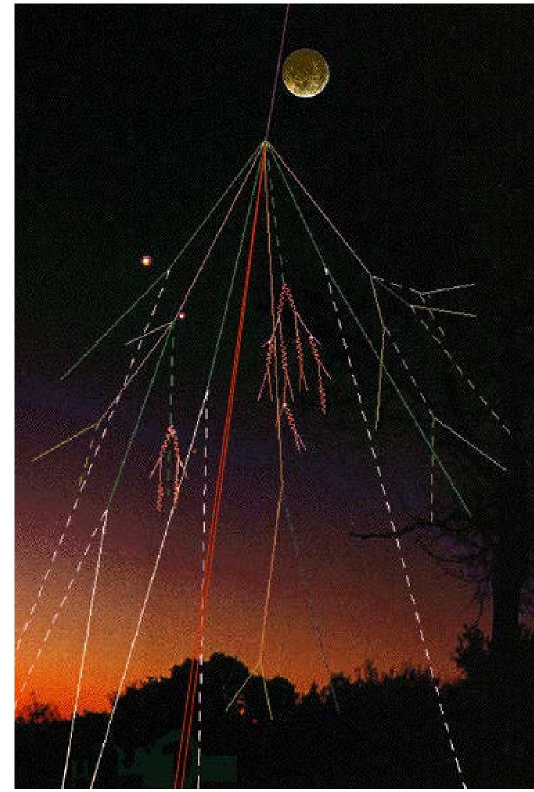
Bombardment of the atmosphere by intense high energetic particle radiation (electrons, protons, and heavy elements) produced and accelerated by the magnetic field of the sun (solar activity cycle) and by distant cataclysmic events such as supernovae.

Origin and nature of cosmic rays



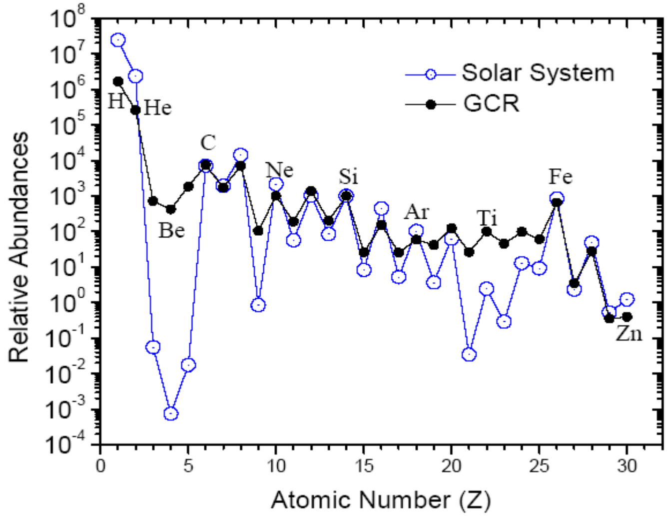


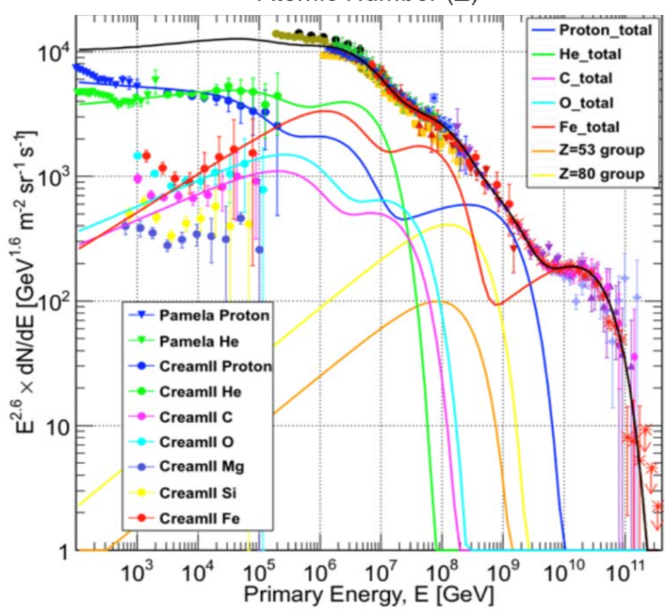


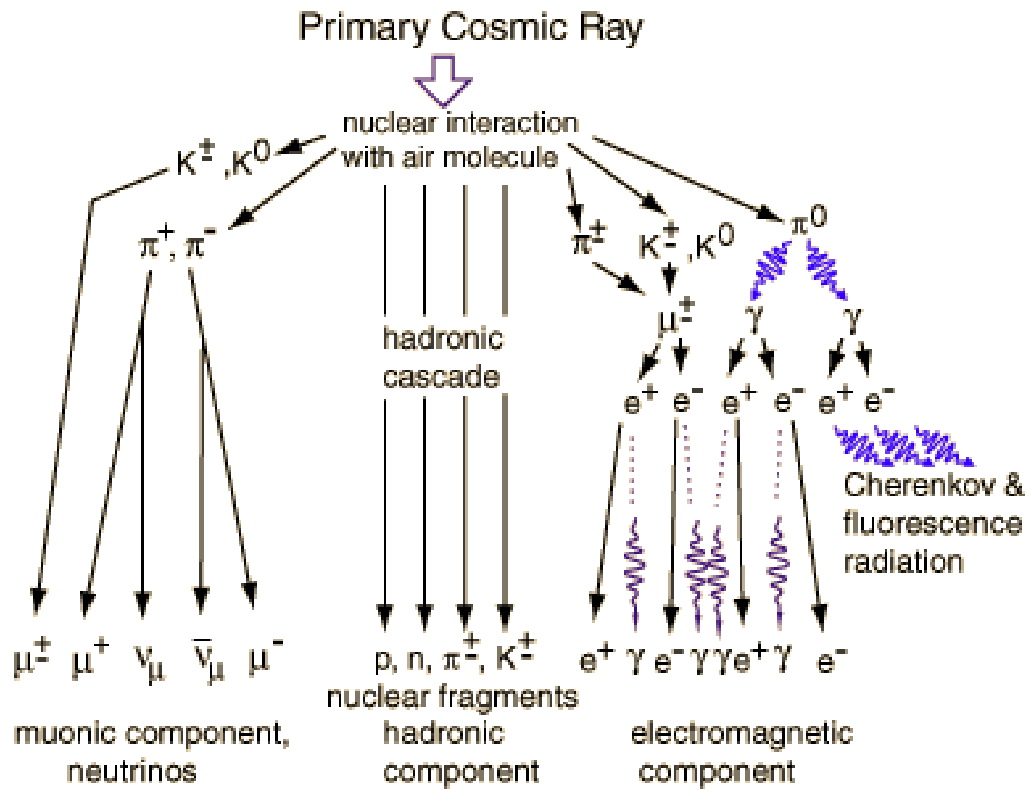


Cosmic rays cover a wide energy range, depending on the source (sun to distant supernova). The cosmic rays cause spallation effects in the atmosphere generating a secondary radiation flux of high energetic and often radioactive particles.

Composition of Cosmic Radiation

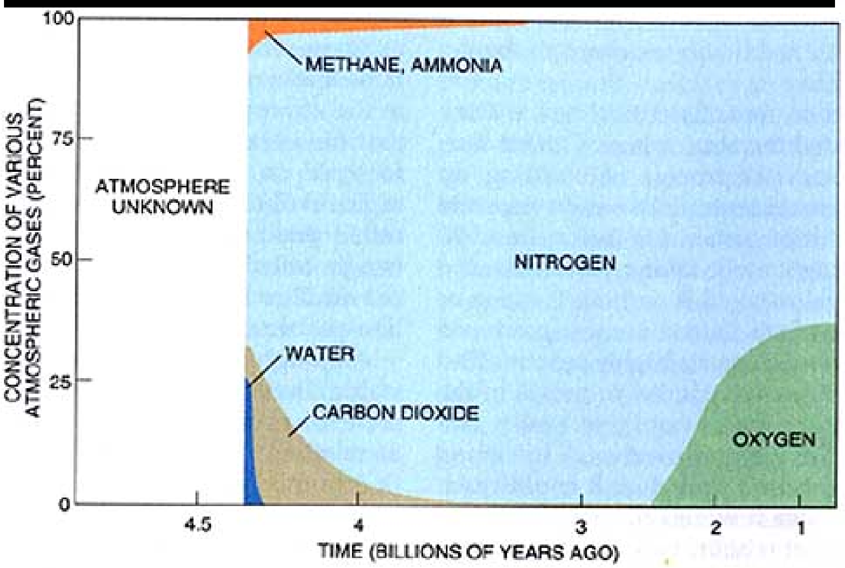


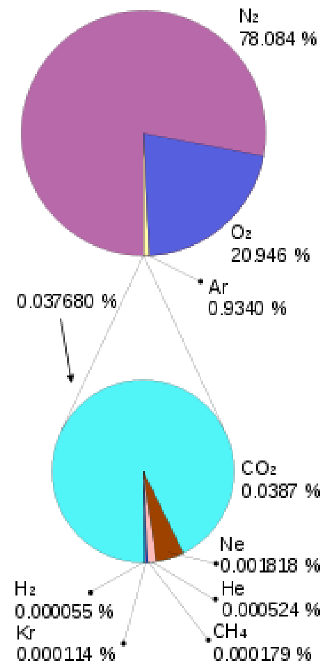




Initial composition changes by spallation reactions generating a high flux of energetic secondary hadronic and elementary particles, the air shower.

Composition of the Atmosphere



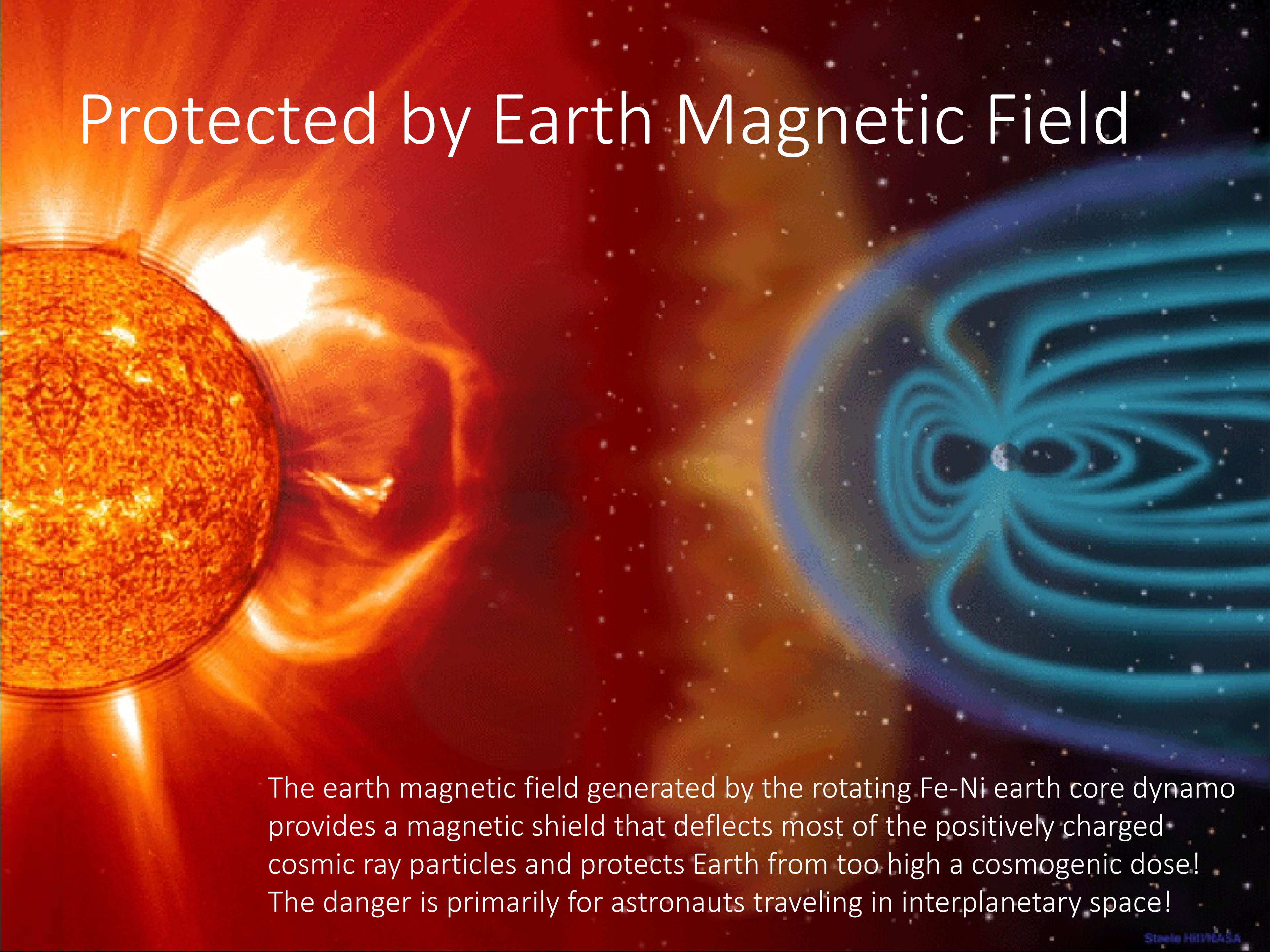


Gas Name	Chemical Formula	Percent Volume
Nitrogen	N_2	78.08%
Oxygen	O_2	20.95%
*Water	H_2O	0 to 4%
Argon	Ar	0.93%
*Carbon Dioxide	CO_2	0.0360%
Neon	Ne	0.0018%
Helium	He	0.0005%
*Methane	CH_4	0.00017%
Hydrogen	H_2	0.00005%
*Nitrous Oxide	N_2O	0.00003%
*Ozone	O_3	0.000004%

* variable gases

The earth atmosphere is not a constant entity, but subject to changes due to geo-chemical processes and developments, radioactive decay induced emissions such as Argon and Helium, and cosmic ray induced reaction processes

Protected by Earth Magnetic Field



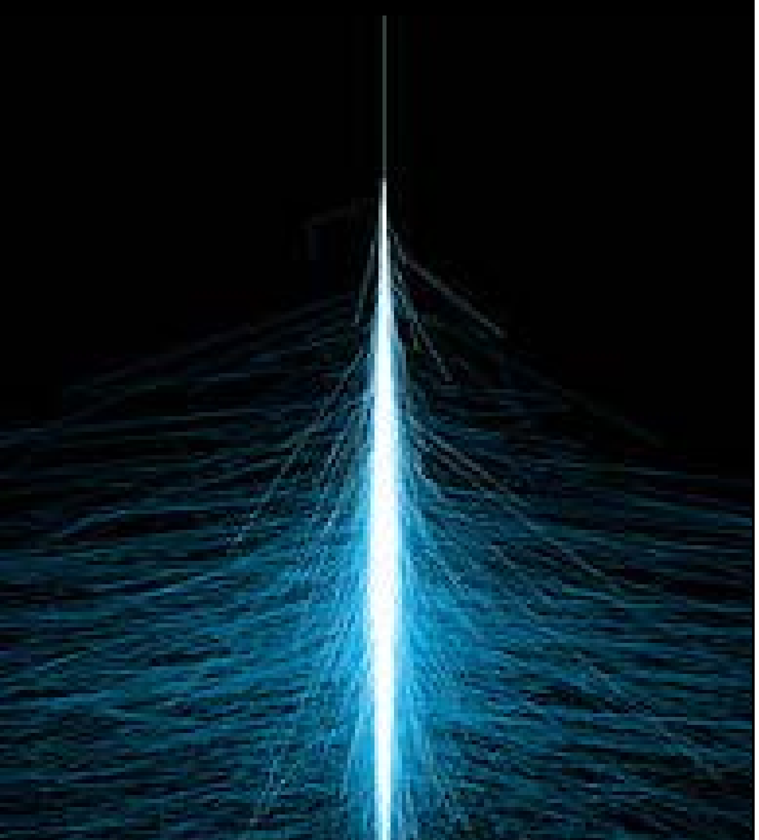
The earth magnetic field generated by the rotating Fe-Ni earth core dynamo provides a magnetic shield that deflects most of the positively charged cosmic ray particles and protects Earth from too high a cosmogenic dose! The danger is primarily for astronauts traveling in interplanetary space!

Cosmic ray induced mutation?

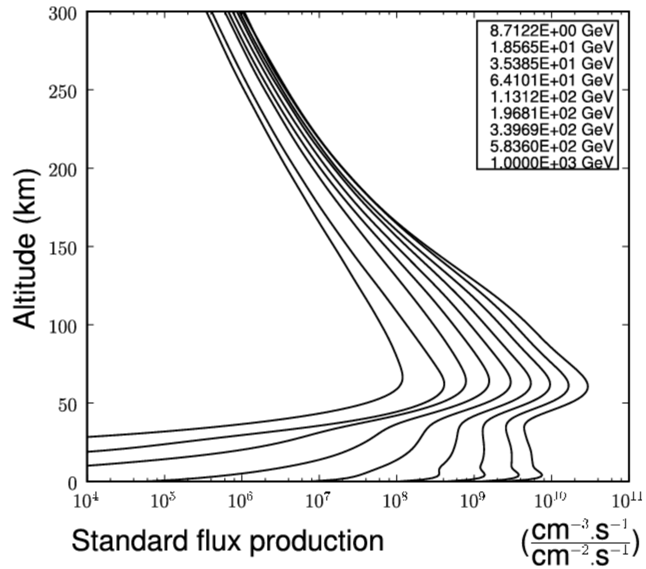
Cosmic ray triggers mutation processes by affecting the molecular structure or sequence of DNA sections, causing the mutations that may have driven the evolution of life.

Cosmic Ray Shower Development

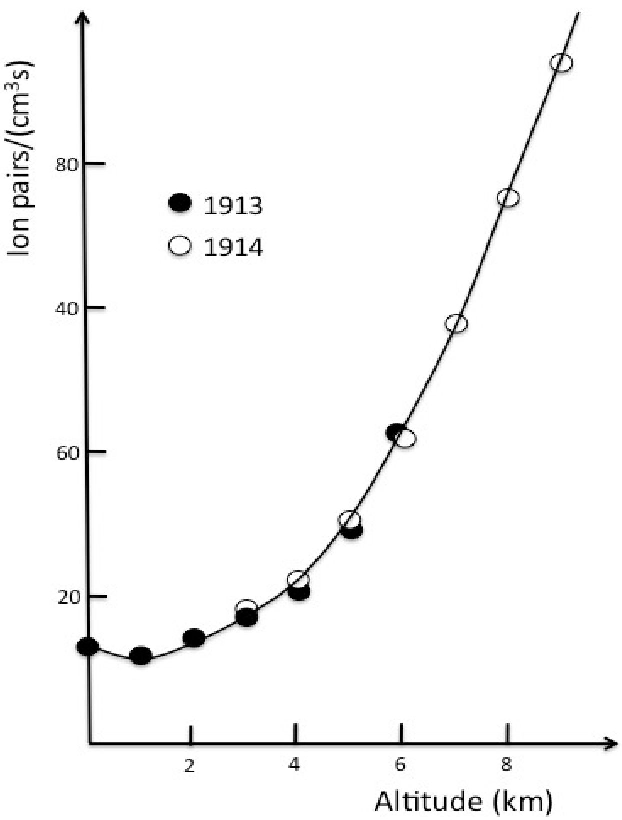
through secondary interaction of cosmic particle in atmosphere



Multiple reactions of incoming high energy particle with air causes spallation of air molecules, atoms, and nuclei and fragmentation of incoming heavy ion components!



High Altitude

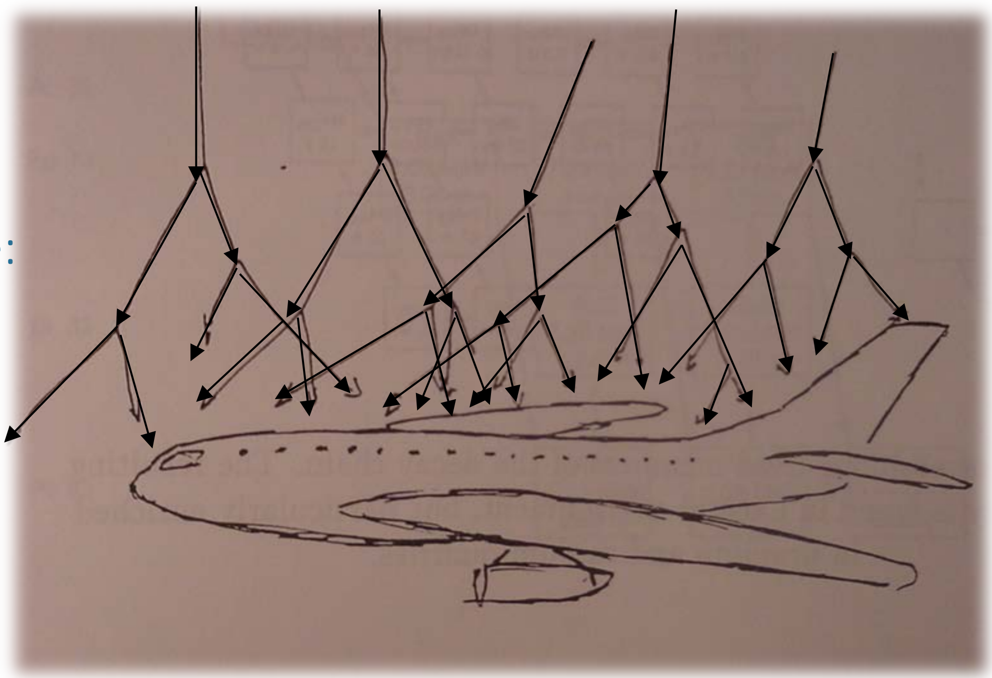


Maximum exposure is near stratospheric altitude because of interaction probability of incoming ray with atmospheric particles. At lower altitudes sea-level to mountain level you experience an increase in cosmic ray exposure roughly doubling with every 1500 m. High exposure to mountain populations, air personnel, and frequent flyers.

Cosmic Rays in High Altitude

Earth is relatively protected from cosmic rays through atmosphere shield; typical exposure is D=0.04 μSv/h. Mountain climbers and airline crews and passengers are exposed to higher doses of radiation. Dose doubles every 1500 m in height. At 1.5 km altitude $D_{(h=1500m)}$=0.08 μSv/h. At 10 km height dose is about 100 times sea-level dose D=5 μSv/h.

$$D_{(h_n = n \cdot 1500m)} = 2^n \cdot D_{(h_0)}$$



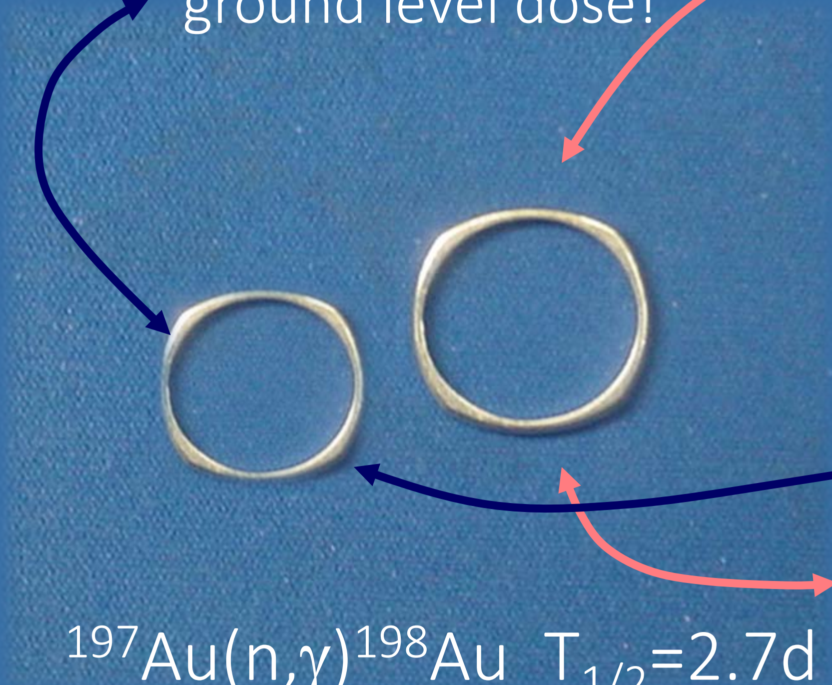
Example: Total dose D:

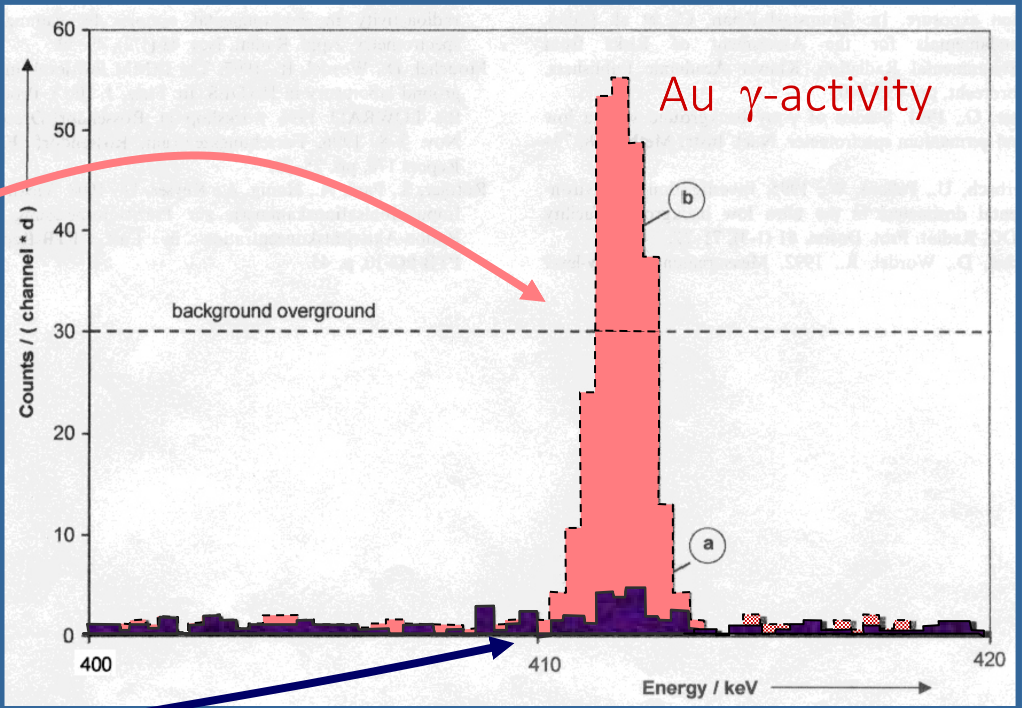
- after 10h of flight in 10km altitude:
  D=2.5 μSv·10h =0.025 mSv,
- for round trip:
  D=0.05 mSv
- Frequent flyer with about
  6 transatlantic flights/year
  D=0.3 mSv/year.

Compare to natural dose (~0.3 mSv/y) !

Observable Effects in Activation by Neutron Capture!

Wife's ring with ground level dose!





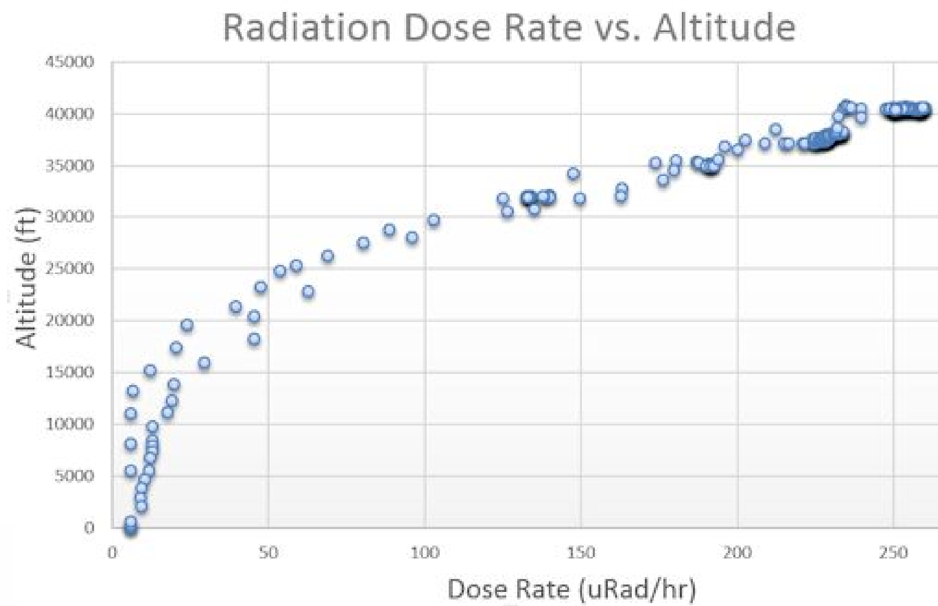
Husband's ring with transatlantic high altitude dose

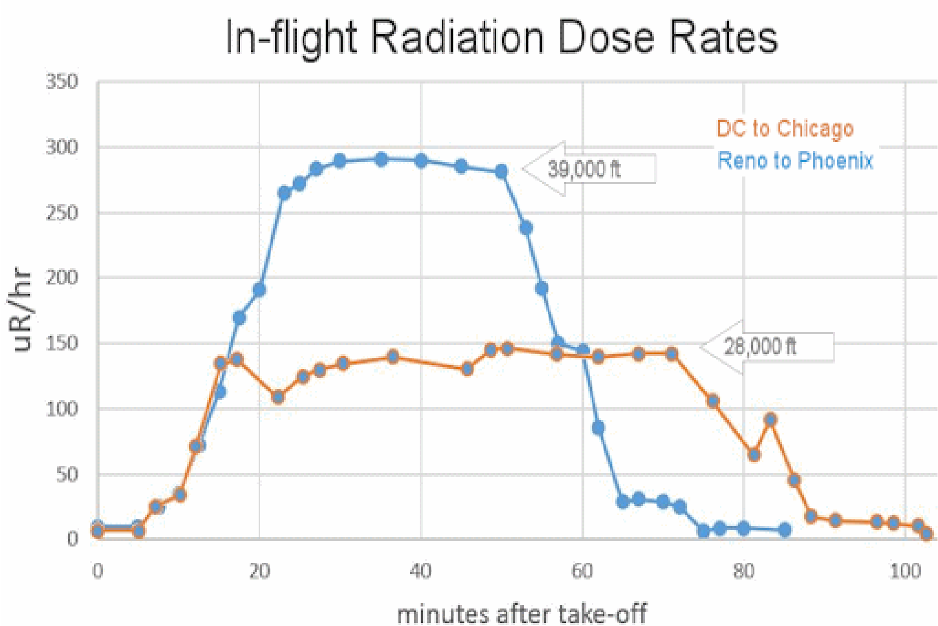
⇨ 8 times more dose

$^{197}Au(n,\gamma)^{198}Au$ $T_{1/2}=2.7d$

$E_\gamma=412$ keV

Radiation Dose per Altitude

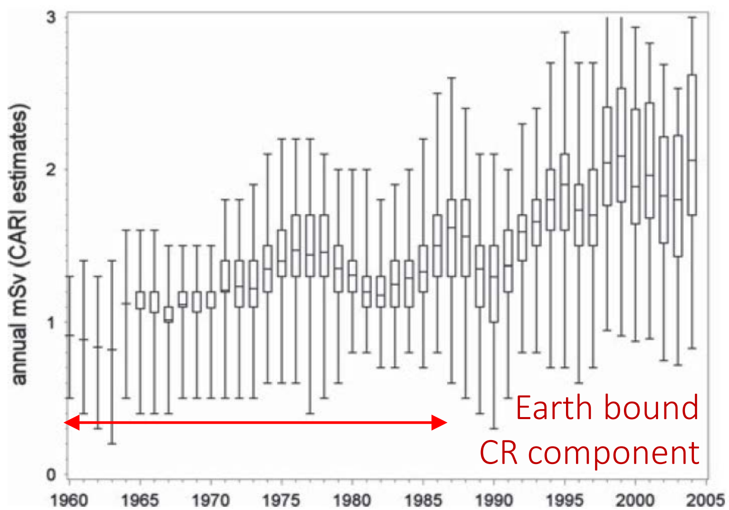


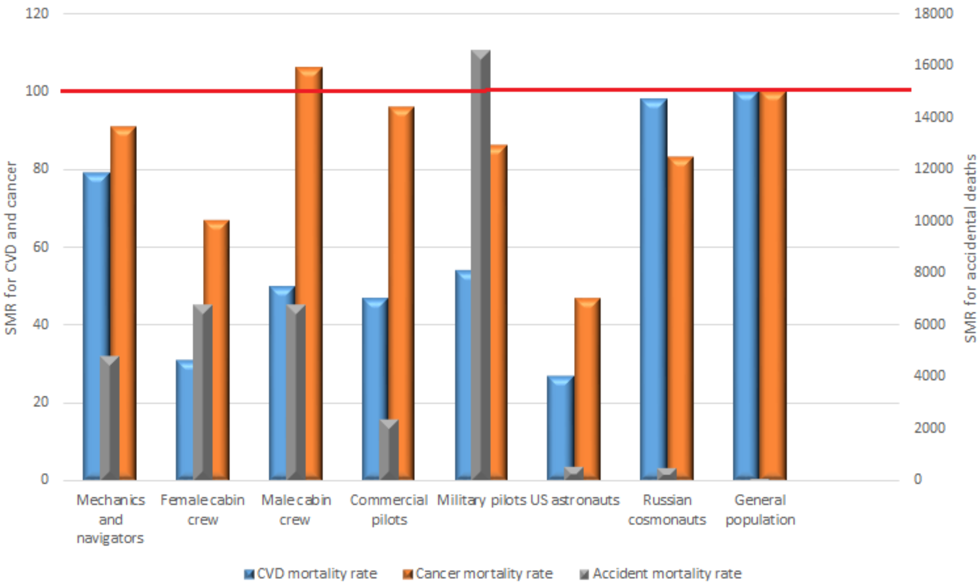


1 Gy = 100 Rad   1 Rad = 0.01 Gy

High altitude flights give you a considerably higher dose. Increasing the altitude by 40% doubles the hourly dose for passenger & crew.

Annual Dose of Air Crew (1960-2005)

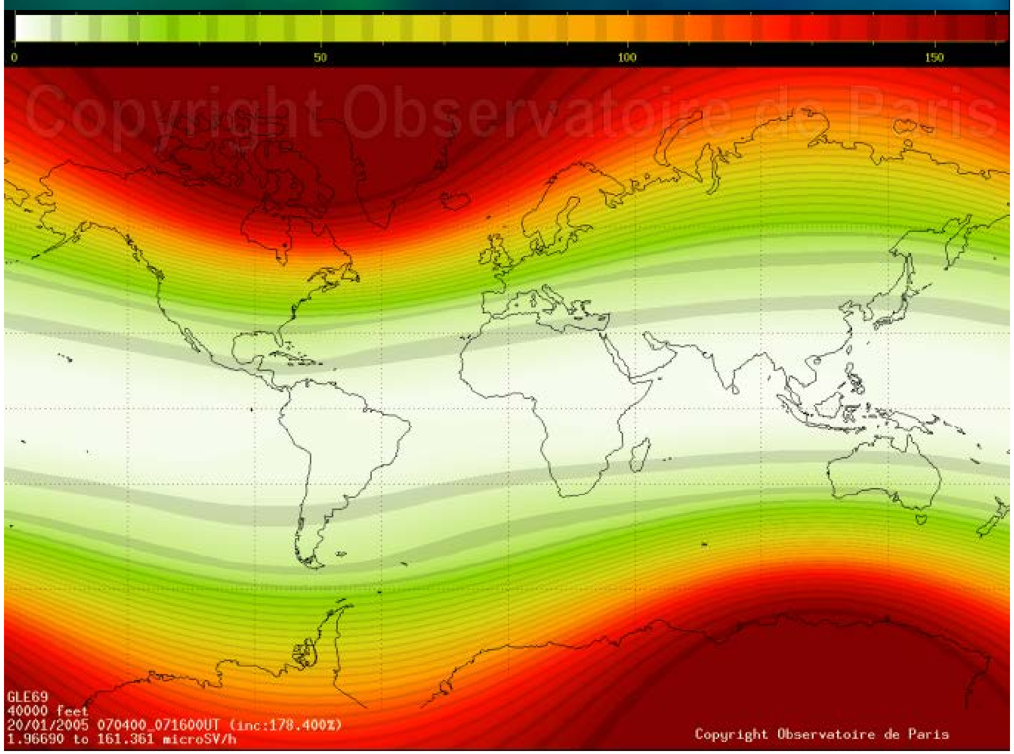


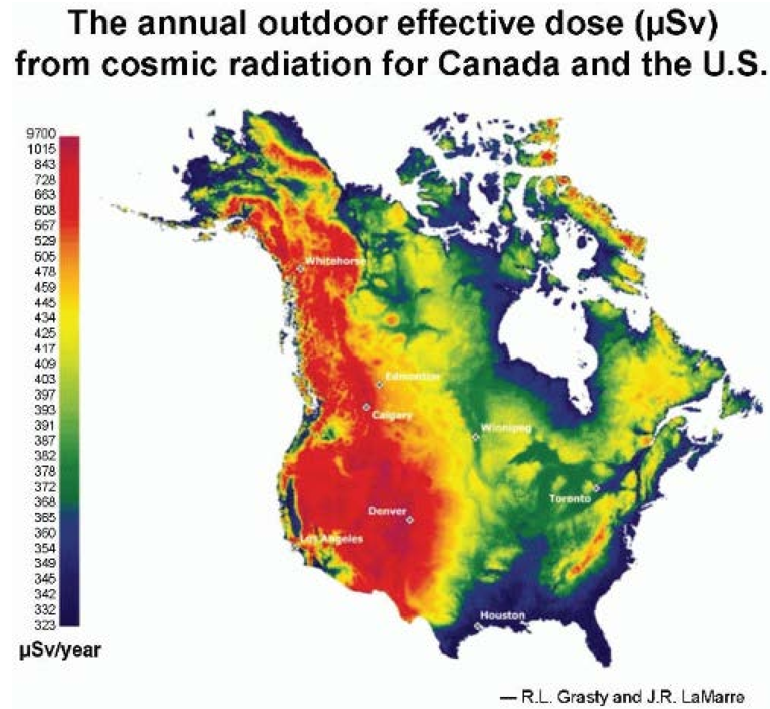


http://www.nrc.gov/about-nrc/radiation/around-us/calculator.cfm

The average CR annual dose of air crew personnel is 1.5 mSv (150 mRem), your annual dose CR in South Bend is: 0.3 mSv (0.03 Rem) The mortality rate of air crews on cancer and other sicknesses is significantly lower in comparison of general population (same age group). No statistically significant increase in cancer rate has been observed.

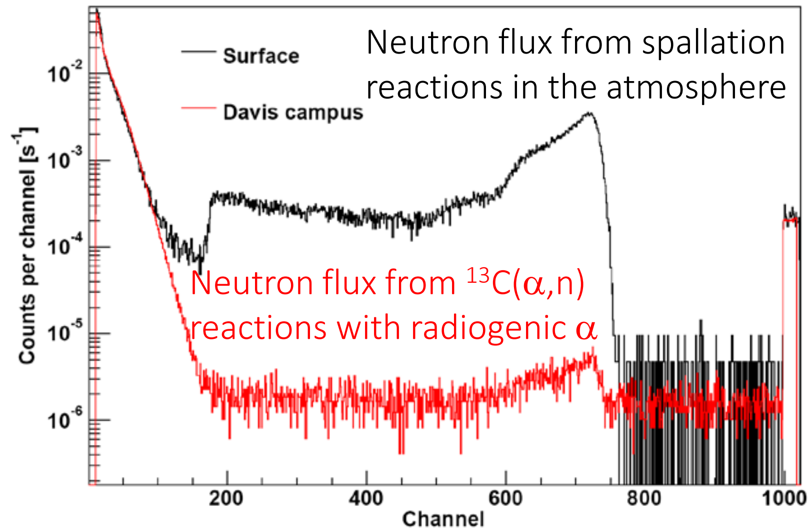
Cosmic Ray Intensity Distribution

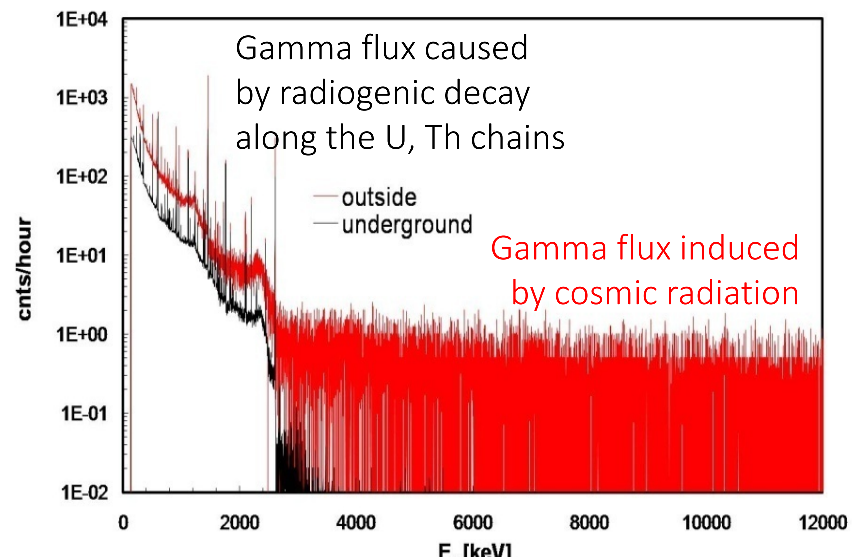




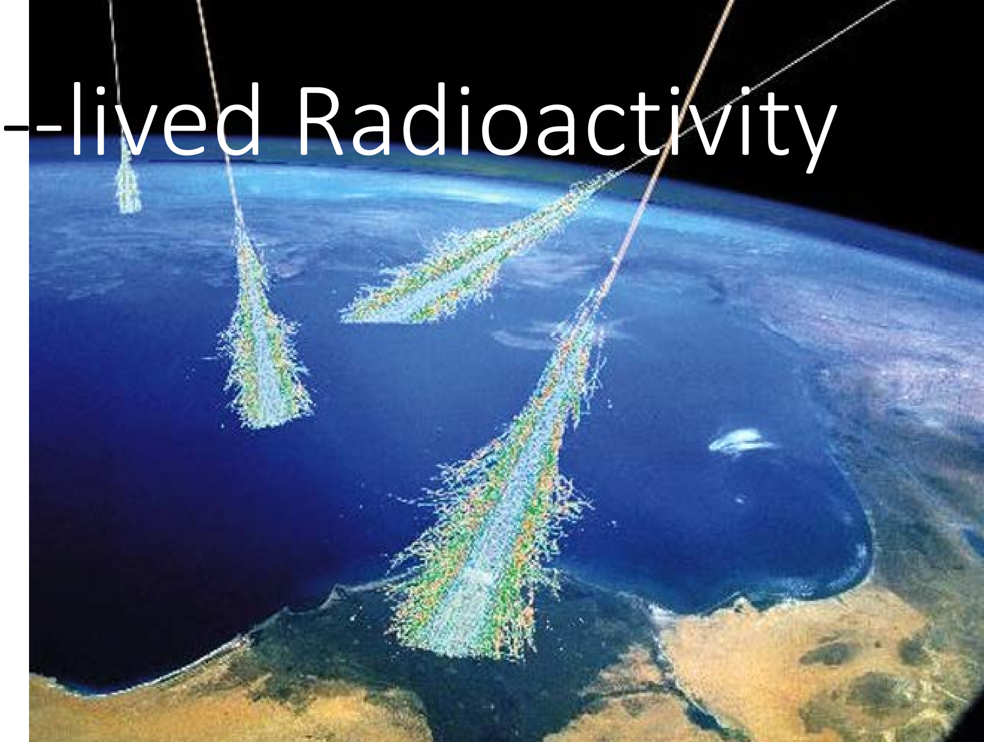
The average annual cosmic ray dose is 0.4 mSv. Higher Dose is associated with altitude but also with the latitude of locations due to the funneling effects of the earth magnetic field.

Rock Shielding Underground

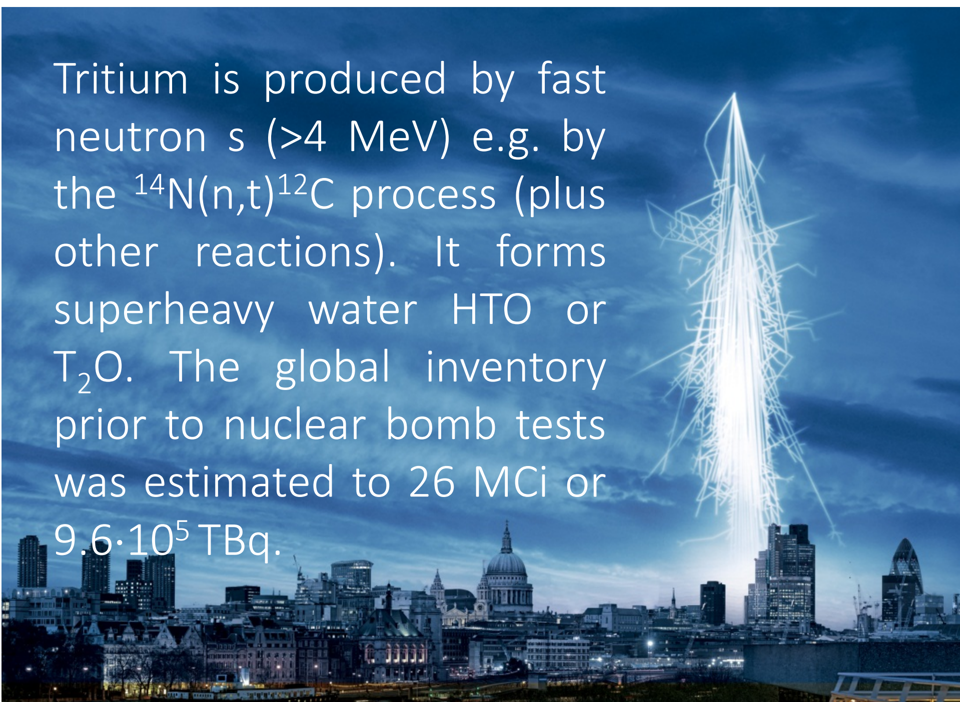




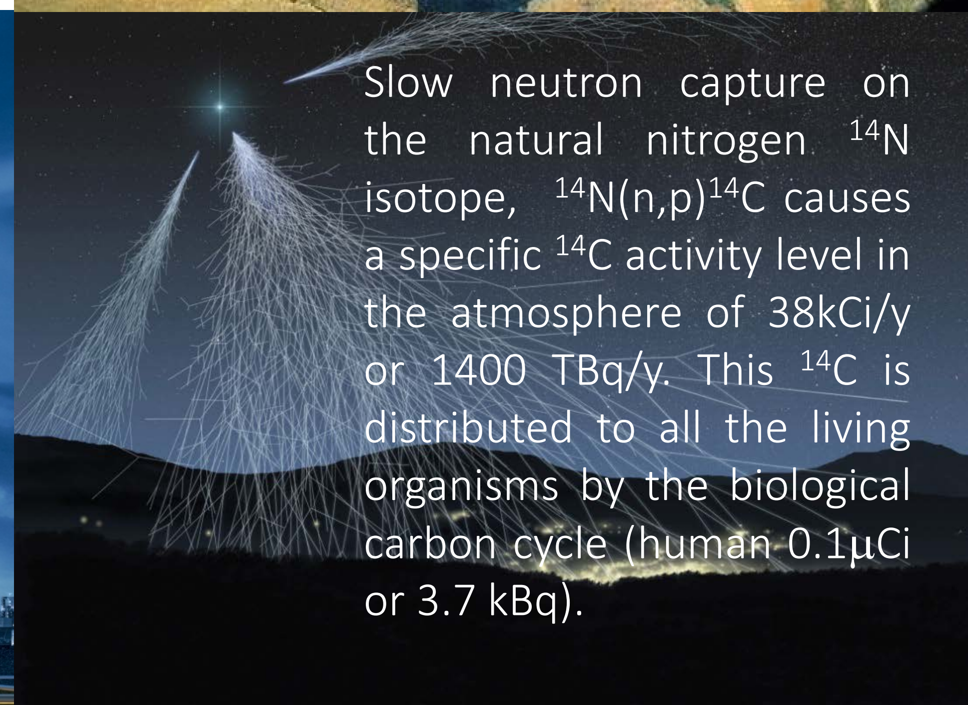
Production of long--lived Radioactivity by Cosmic Rays



Primary radioactive products of cosmic ray spallation are ^{3}H (tritium) $T_{1/2}$=12y) and ^{14}C ($T_{1/2}$=5730y). Spallation occurs mainly on ^{14}N and ^{40}Ar isotopes in the atmosphere, the increase of radiogenic Ar caused an increase of cosmic rays induced radioactivity.



Tritium is produced by fast neutron s (>4 MeV) e.g. by the $^{14}N(n,t)^{12}C$ process (plus other reactions). It forms superheavy water HTO or T_2O. The global inventory prior to nuclear bomb tests was estimated to 26 MCi or $9.6 \cdot 10^{5}$ TBq.

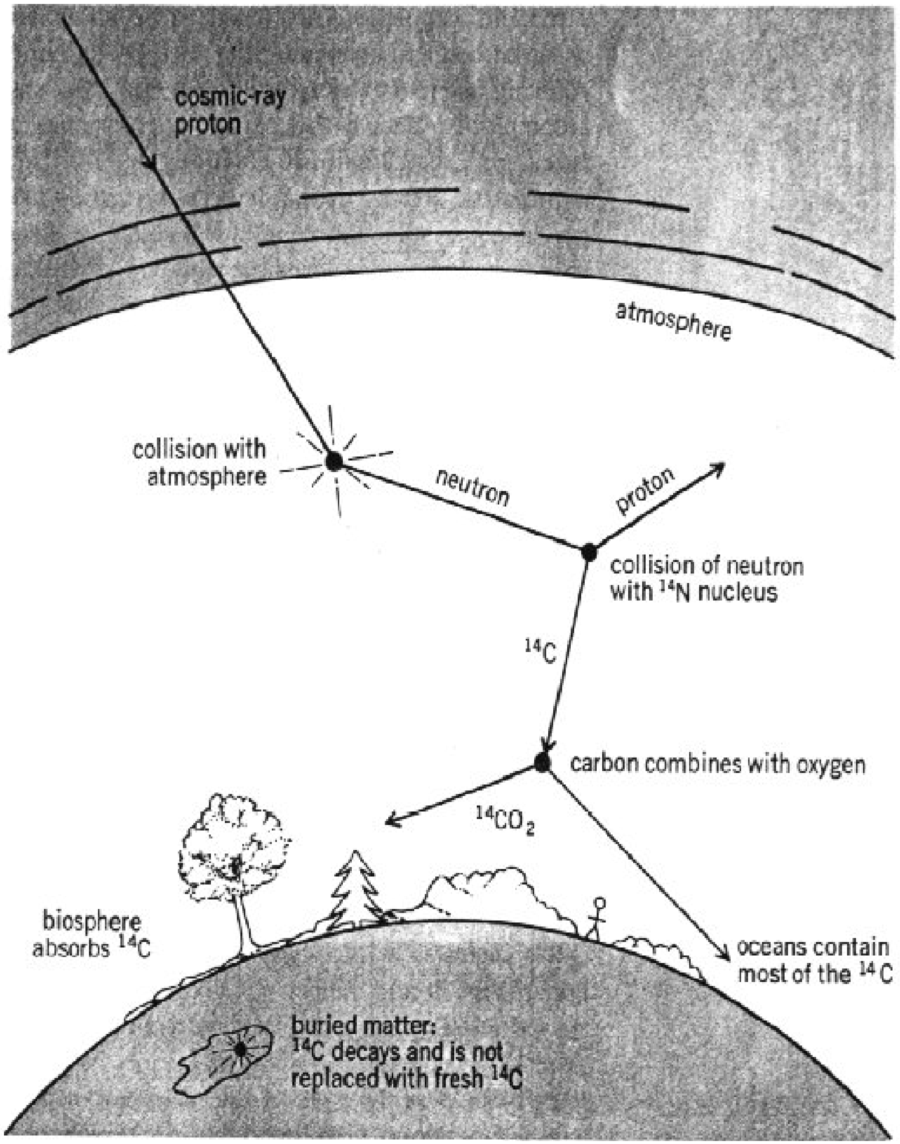


Slow neutron capture on the natural nitrogen ^{14}N isotope, $^{14}N(n,p)^{14}C$ causes a specific ^{14}C activity level in the atmosphere of 38kCi/y or 1400 TBq/y. This ^{14}C is distributed to all the living organisms by the biological carbon cycle (human 0.1μCi or 3.7 kBq).

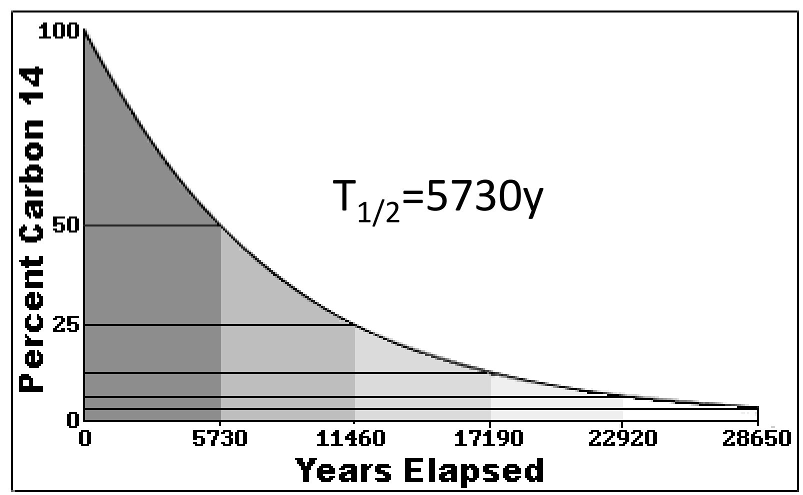
Cosmic Ray induced radionuclides in the atmosphere, materials, and creatures

Radio-nuclide	Half-life	Major Radiations	Target Nuclides	Typical Concentrations, Bq/kg		
				Air (troposphere)	Rain Water	Ocean Water
^{10}Be	1,600,000 y	β	N, O	--	--	2×10^{-8}
^{26}Al	716,000 y	γ	Ar	--	--	2×10^{-10}
^{36}Cl	300,000 y	β	Ar	--	--	1×10^{-5}
^{81}Kr	229,000 y	K x rays	Kr	--	--	--
^{14}C	5730 y	β	N, O	--	--	5×10^{-3}
^{32}Si	172 y	β	Ar	--	--	4×10^{-7}
^{39}Ar	269 y	β	Ar	--	--	6×10^{-8}
^{3}H	12.33 y	β	N, O	1.2×10^{-3}	--	7×10^{-4}
^{22}Na	2.60 y	β^+	Ar	1×10^{-6}	2.8×10^{-4}	--
^{35}S	87.51 d	β	Ar	1.3×10^{-4}	7.7×10^{-3} – 107×10^{-3}	--
^{7}Be	53.29 d	γ	N, O	0.01	0.66	--
^{37}Ar	35.0 d	K x rays	Ar	3.5×10^{-5}	--	
--	^{33}P	25.3 d	β	Ar	1.3×10^{-3}	--
^{32}P	14.26 d	β	Ar	2.3×10^{-4}	--	--
^{28}Mg	20.91 h	β	Ar	--	--	--
^{24}Na	14.96 h	β	Ar	--	3.0×10^{-3} – 5.9×10^{-3}	--
^{38}S	2.84 h	β	Ar	--	6.6×10^{-2} – 21.8×10^{-2}	--
^{31}Si	2.62 h	β	Ar	--	--	--
^{18}F	1.83 h	β^+	Ar	--	--	--
^{39}Cl	55.6 m	β	Ar	--	1.7×10^{-1} – 8.3×10^{-1}	--
^{38}Cl	37.24 m	β	Ar	--	1.5×10^{-1} – 25×10^{-1}	--
^{34m}Cl	32.0 m	β^+	Ar	--	--	--

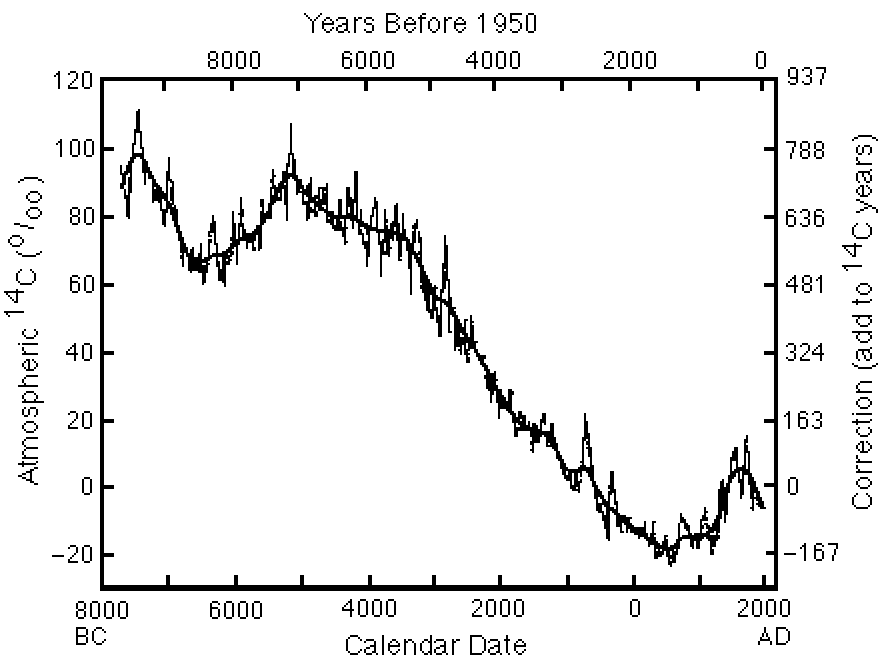
^{14}C Enrichment in Environment

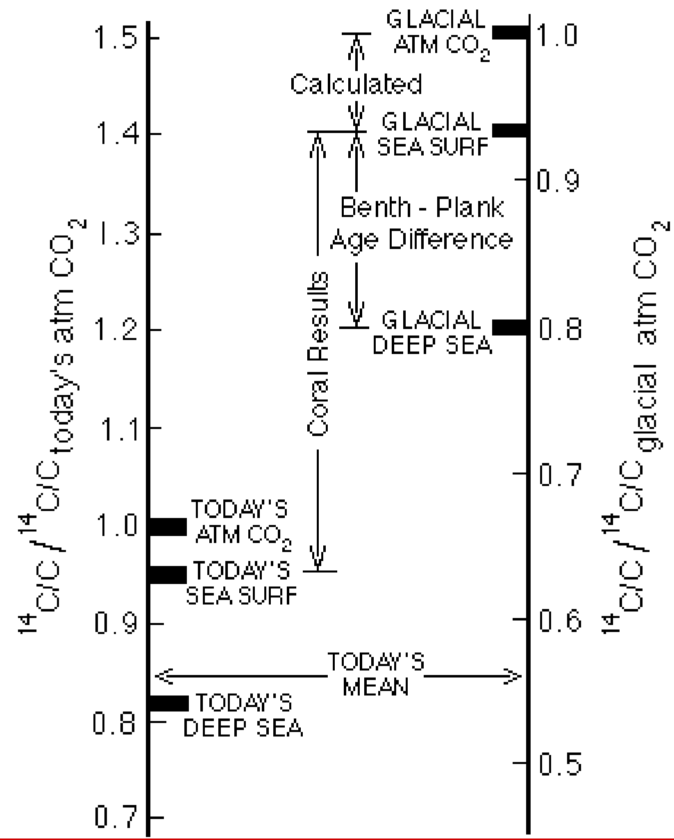


^{14}C is produced by the interaction of cosmic rays induced neutrons with ^{14}N in the atmosphere through the $^{14}N(n,p)^{14}C$ reaction. The ^{14}C behaves chemically like regular carbon and is implemented in regular carbon cycle with an abundance that depends on the production rate. This depends on the cosmic ray flux, the abundance of ^{14}N in the atmosphere and the reaction probability. The ^{14}C decays but is continuously replenished by solar activity



$^{14}C/^{12}C$ Ratio in Atmosphere



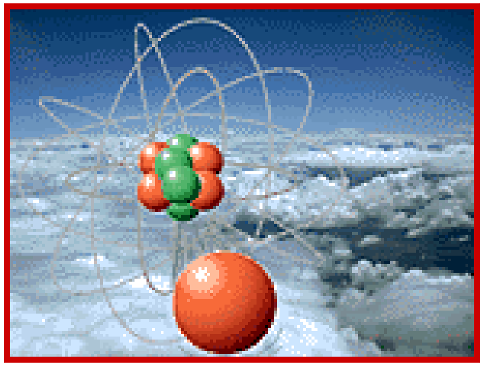


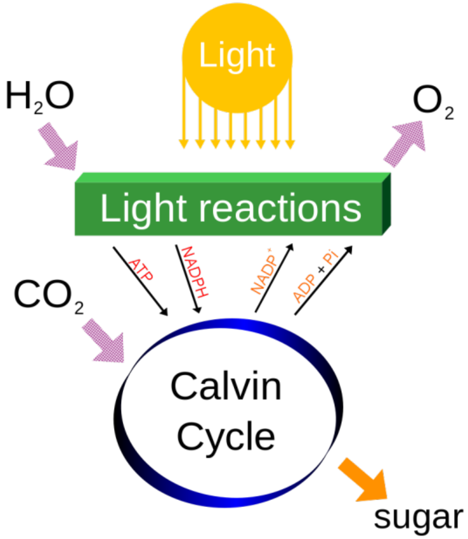
Based on ice-and tree-ring calibrations it was determined that $^{14}C/^{12}C$ ratio is not constant with time, but shows long term fluctuations!

The fluctuation are due to solar distance and direction, variation in earth magnetic field, climatic conditions and more recently traffic and industry due to burning of fossil fuel with zero ^{14}C content.

Average ratio: $^{14}C/^{12}C=1.3\cdot10^{-12}$

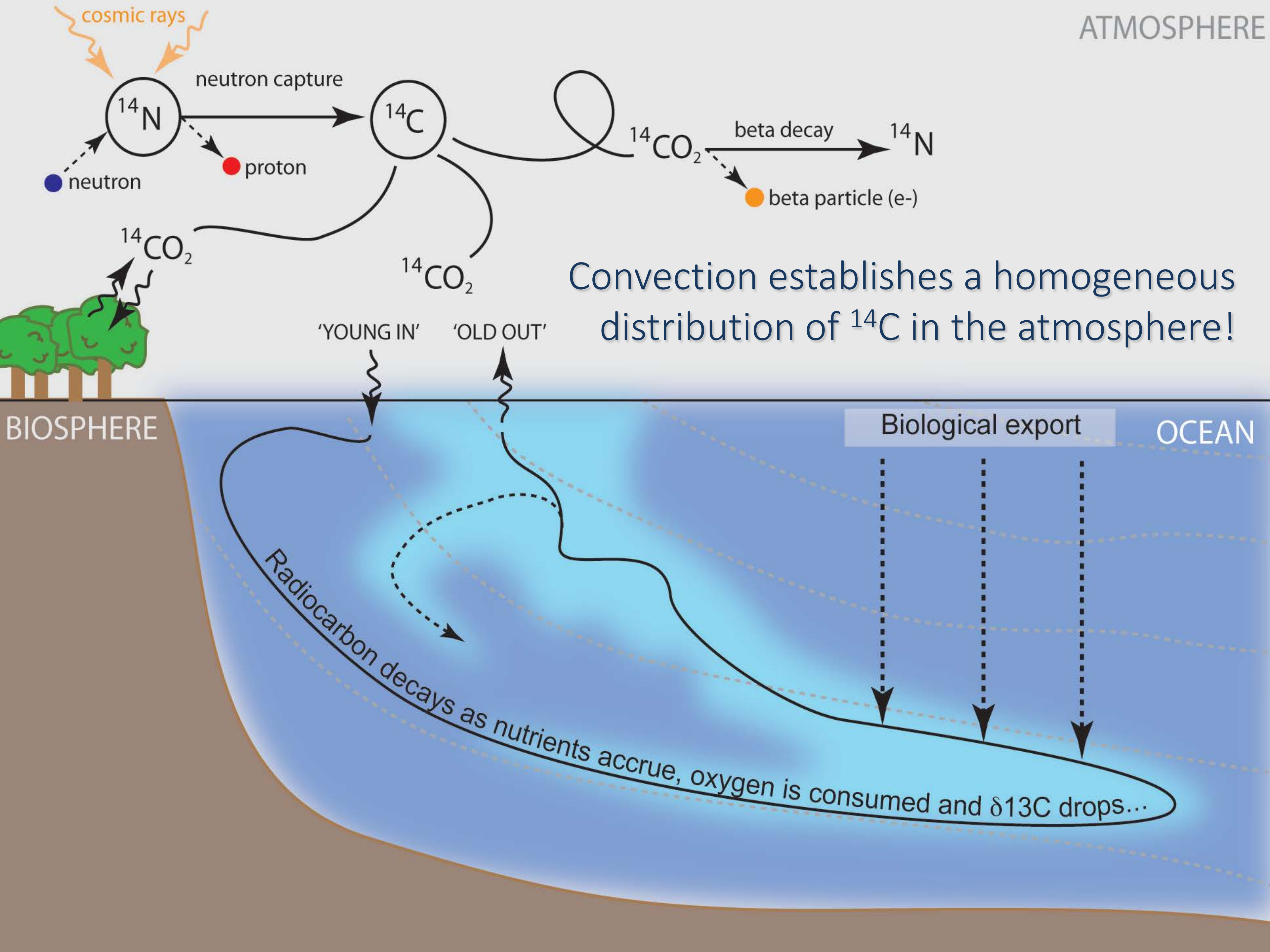
^{14}C Content in Atmosphere and Human



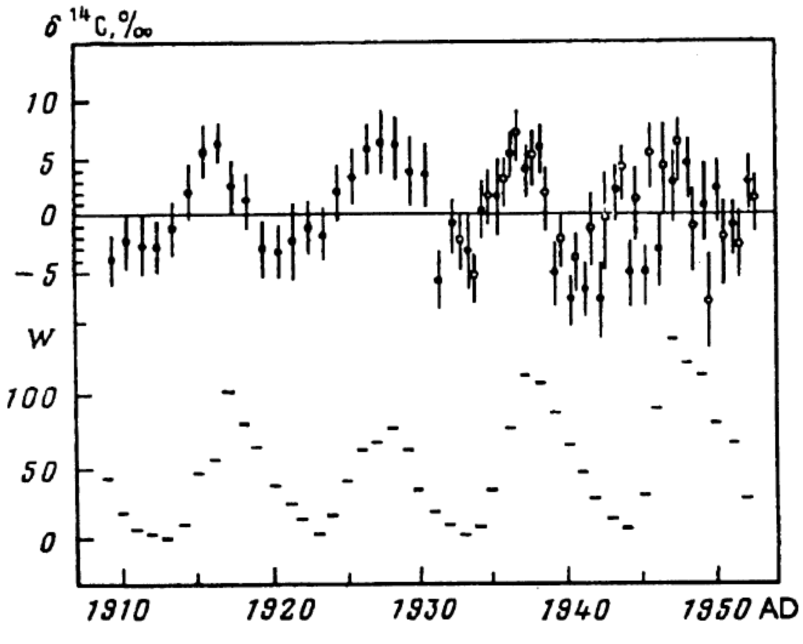


The production rate of ^{14}C due to the $^{14}N(n,p)^{14}C$ process is about 22000 ^{14}C-Isotopes per second and square meter. Taking the decay constant of $\lambda = \ln 2/5730\ y = 1.21 \cdot 10^{-4}\ y^{-1}$, the production of ^{14}C-radioaktivity is approximately 2.66 Bq/y m^2. That translates into an annual production of 1.4 PBq, 1400 Trillion Becquerel in the earth atmosphere. This radioactivity becomes part of the biological carbon cycle.

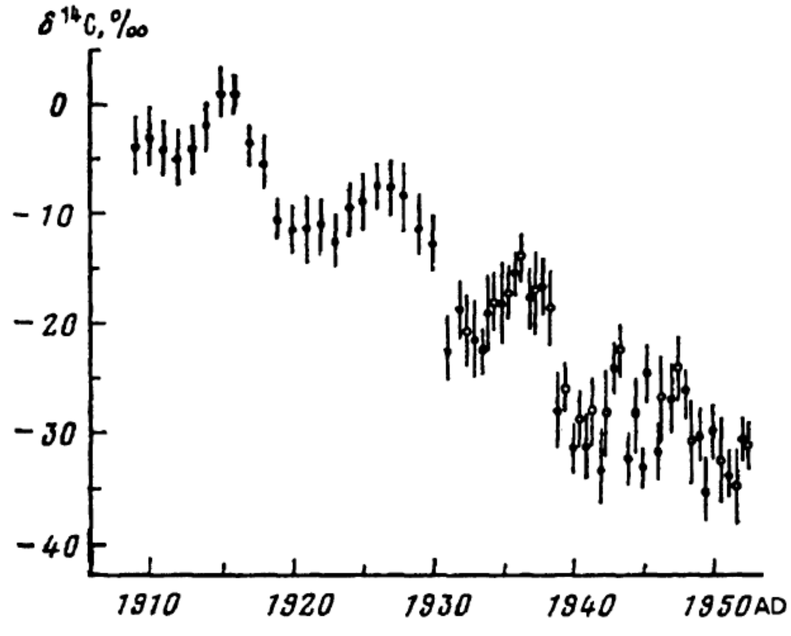
- It forms $^{14}CO_2$ by chemical reaction with atmospheric oxygen
- It is absorbed by plants through photosynthesis with the ^{14}C becoming part of the plant chemistry
- It is eaten by man or cow becoming part of the human body system


ATMOSPHERE
cosmic rays
^{14}N
neutron capture
^{14}C
neutron
proton
$^{14}CO_2$
beta decay
^{14}N
beta particle (e-)
$^{14}CO_2$
$^{14}CO_2$
Convection establishes a homogeneous distribution of ^{14}C in the atmosphere!
'YOUNG IN'
'OLD OUT'
BIOSPHERE
Biological export
OCEAN
Radiocarbon decays as nutrients accrue, oxygen is consumed and δ13C drops...

Short-term fluctuations of the $^{14}C/^{12}C$ Ratio in Atmosphere

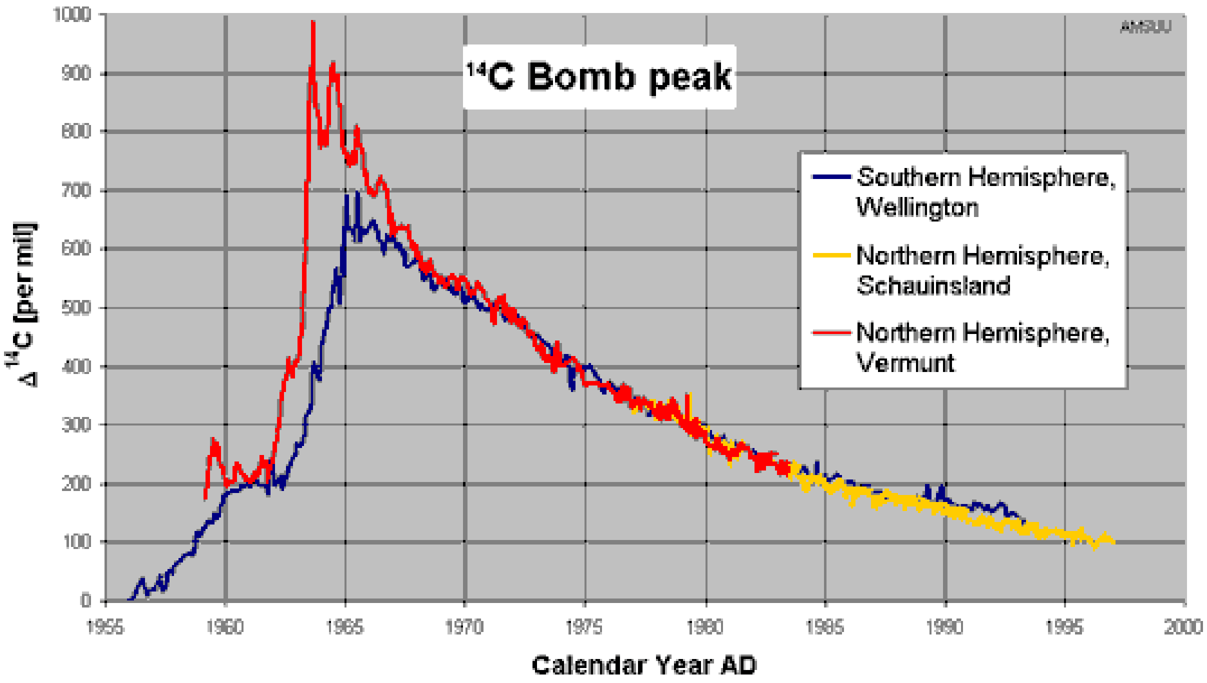


Fluctuation of ^{14}C content in vintage wine (upper curve) due the 11 year cycle of solar activity that provides the cosmic ray flux (lower curve) responsible for the ^{14}C production. The ^{14}C curve is normalized to a constant value for better comparison.



Un-normalized curve of ^{14}C in vintage wine, the overall decline in ^{14}C content reflects the increase of carbon emission from fossil (old) fuel burning deposited into the atmosphere and in due turn into the wine.

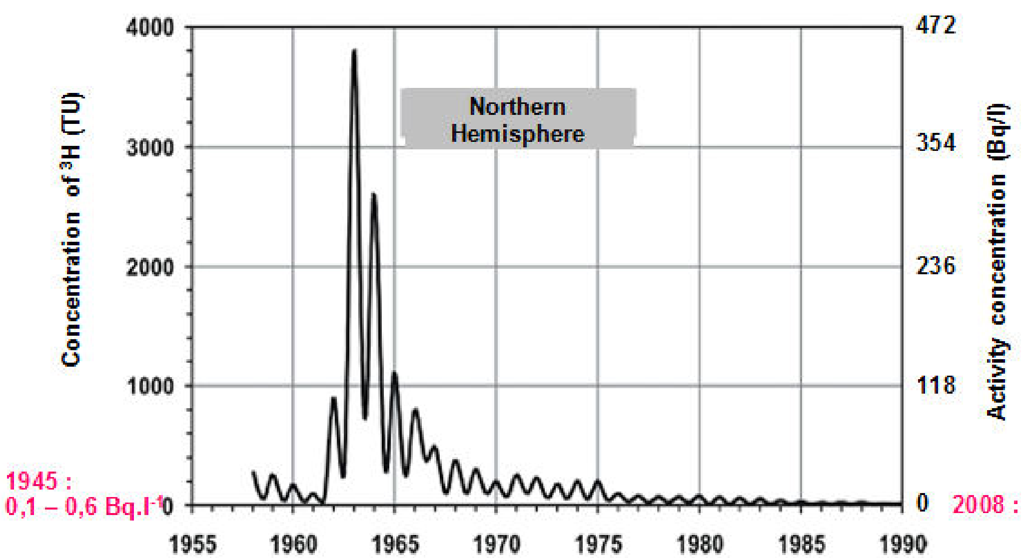
Anthropogenic ^{14}C fluctuation



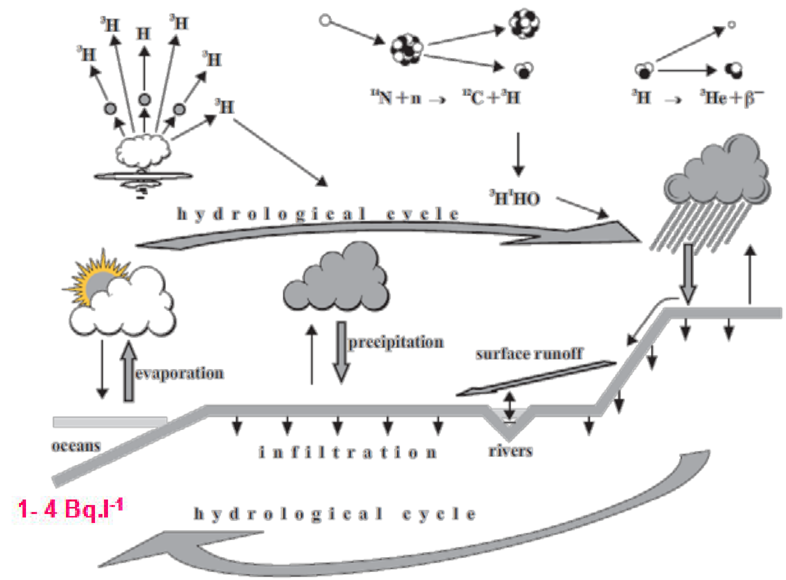
The physical half-life of ^{14}C is 5730 years but the produced ^{14}C activity is falling off much faster with an half life of about 10 years. This reflects the absorption capability of the earth environmental system, ocean, plants, animals.

Tritium Production and the Tritium Peak

Pre-war cosmic ray bombarded generated natural tritium via the reaction $^{14}N(n,t)^{12}C$ at a rate of 0.1-0.6Bq/l. In equilibrium between production and decay, the average annual production of tritium in the atmosphere is $72 \cdot 10^{15}$ Bq or 72 PBq. The tritium isotope couples chemically with oxygen forming heavy radioactive water that participates at the water cycle in the hydrosphere. The average tritium activity in the atmosphere is 1 Exa-Becquerel or a quintillion (10^{18}) Becquerel. 90% in water and 10% in water vapor or clouds. The ratio of tritium to hydrogen is defined in TU: 1 TU is the *ratio* of 1 *tritium* to 10^{18} *hydrogen* atoms.



Smooth curve showing the average ^3H concentrations in precipitation over the continental surface in the Northern hemisphere. ***Source = IAEA Isotope hydrology, 2006***



Other cosmogenic radioactive isotopes that impact the average radiation exposure

Radionuclides Induced in the Earth's Atmosphere by Cosmic Rays[a]

Radionuclide	Half-life	Major radiations	Target nuclides	Typical concentrations (Bq kg^{-1})[b]		
				Air (troposphere)	Rainwater	Ocean water
^{10}Be	1,600,000 y	β	N, O			2×10^{-8}
^{26}Al	720,000 y	β^+	Ar			2×10^{-10}
^{36}Cl	300,000 y	β	Ar			1×10^{-5}
^{80}Kr	213,000 y	K X ray	Kr			
^{14}C	5730 y	β	N, O			5×10^{-3}
^{32}Si	~650 y	β	Ar			4×10^{-7}
^{39}Ar	269 y	β	Ar			6×10^{-8}
^{3}H	12.33 y	β	N, O	1.2×10^{-3}		7×10^{-4}
^{22}Na	2.60 y	β^+	Ar	1×10^{-6}	2.8×10^{-4}	
^{35}S	87.4 d	β	Ar	1.3×10^{-4}	$7.7–107 \times 10^{-3}$	
^{7}Be	53.3 d	γ	N, O	0.01	0.66	
^{37}Ar	35.0 d	K X ray	Ar	3.5×10^{-5}		
^{33}P	25.3 d	β	Ar	1.3×10^{-3}		
^{32}P	14.28 d	β	Ar	2.3×10^{-4}		
^{38}Mg	21.0 h	β	Ar			
^{24}Na	15.0 h	β	Ar		$3.0–5.9 \times 10^{-3}$	
^{38}S	2.83 h	β	Ar		$6.6–21.8 \times 10^{-2}$	
^{31}Si	2.62 h	β	Ar			
^{18}F	109.8 m	β^+	Ar			
^{39}Cl	56.2 m	β	Ar		$1.7–8.3 \times 10^{-1}$	
^{38}Cl	37.29 m	β	Ar		$1.5–25 \times 10^{-1}$	
^{34m}Cl	31.99 m	β^+	Ar			

[a]Adapted from NCRP (1987a); Perkins and Nielson (1965). Reproduced from *Health Physics* Vol. 11, by permission of the Health Physics Society.
[b]One Bq = 27 pCi.