The Role of Radioactive Isotopes in the Formation and Evolution of Terrestrial Planets

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What Are Radioisotopes?

Radioisotopes are the radioactive isotopes of an element. They are also described as atoms with extra energy in their nucleus or an unstable mixture of protons and neutrons. The number of protons in the atomic nuclei of different isotopes of the same element is the same, but the number of neutrons varies.

SHORT LIVED RADIOISOTOPES	LONG LIVED RADIOISOTOPES
^{26}Al	^{40}K
^{60}Fe	^{232}Th
	^{235}U
	^{238}U

^{40}**K** is the most abundant among the four long-lived radioisotopes. It also contributes most of the radiogenic heat of the core. It's decay branches are **β^- decay** directly to the ground state of ^{40}**Ca** and **β^+** branch which produces ^{40}**Ar** by electron capture.

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.31\ \mathrm{MeV},$$

$$^{40}\mathrm{K} + e^- \rightarrow {}^{40}\mathrm{Ar} + \nu_e + 1.51\ \mathrm{MeV}$$

^{232}**Th** is the radioisotope with the longest half-life among the four long-lived radioisotopes ($T_{1/2} \approx 14$ Gy). It is the only isotope of Th that exists now in considerable numbers. It has a long decay chain consisting of several **α and β^- decays**. The long decay chain includes ^{212}Bi which has two decay branches: it can decay via the α branch (I=0.3593) to ^{208}**Tl** or via the β^- branch (I=0.6407) to ^{212}**Po**. The final stable daughter of ^{232}**Th** is 208Pb. Each decay of ^{232}**Th** eventually also produces 6 atoms of 4He.

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\,{}^{4}\mathrm{He} + 4e^- + 4\bar{\nu}_e + 42.7\ \mathrm{MeV}$$

^{235}U is less abundant and shorter-lived ($T_{1/2}$=704 My. compared to the isotope of **^{238}U.** It has a longer and complex decay chain compared to that of **^{232}Th**. The decay chain includes the β^- decays of **^{231}Th, ^{227}Ac, ^{223}Fr, ^{211}Pb, and ^{207}Tl.** The final stable daughter of **^{235}U** is **208Pb**. Each decay of **^{235}U** eventually also produces 7 atoms of 4He.

$$^{235}U \rightarrow \ ^{207}Pb + 7\,^{4}He + 4e^- + 4\bar{\nu}_e + 46.0\ MeV$$

^{238}U is more abundant and has a higher half-life compared to that of ^{235}U ($T_{1/2}$=704 My. It also has a long and complex decay chain. The decay chain includes the β^- decays of ^{234}Th, ^{234}Pa^{m} and ^{234}Pa, ^{218}Po, ^{214}Pb, ^{214}Bi, ^{210}Tl, ^{210}Pb, and ^{210}Bi. The final stable daughter of ^{238}U is ^{208}Pb. Each decay of ^{238}U eventually also produces 8 atoms of ^{4}He.

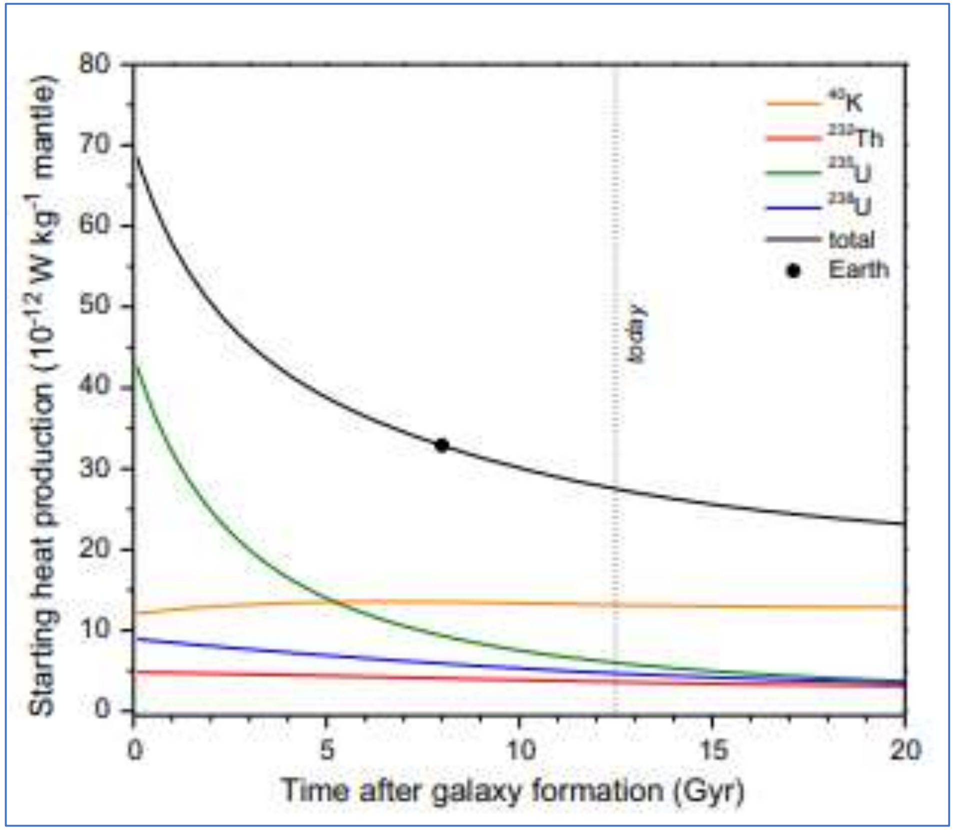
$$^{238}U \rightarrow \ ^{206}Pb + 8\,^{4}He + 6e^- + 6\bar{\nu}_e + 51.7\ MeV$$

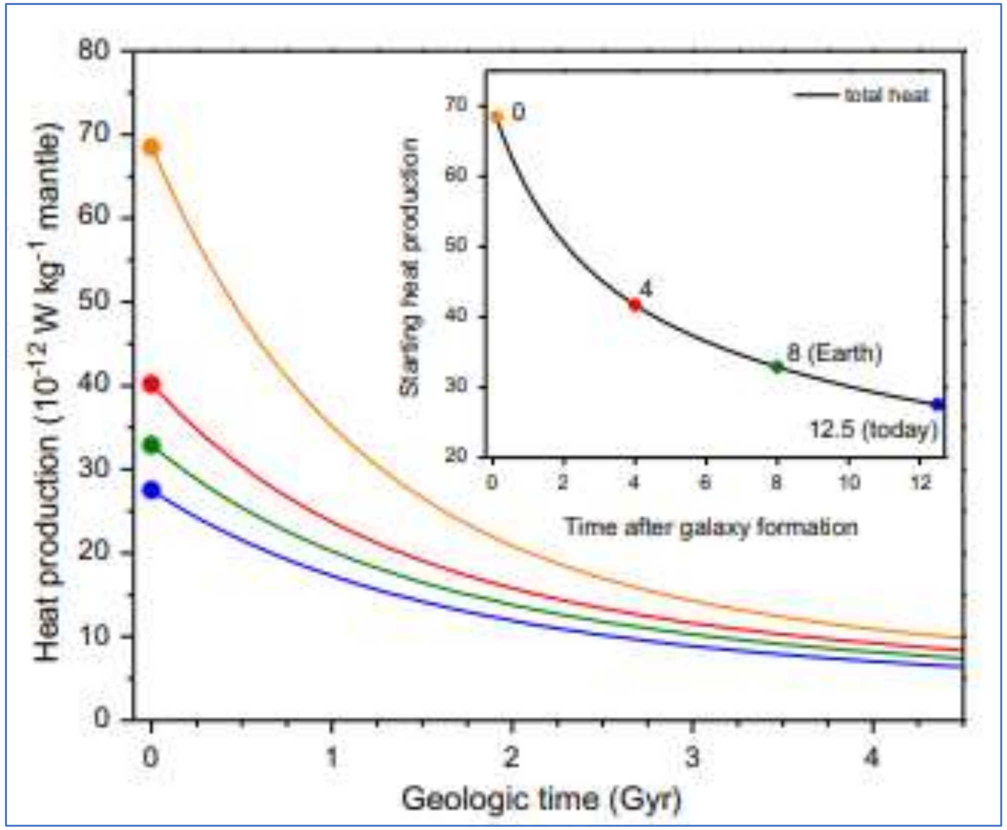
Half-Life is the time required for one-half of the atomic nuclei of a radioactive sample to decay.

RADIOISOTOPES	HALF LIVES $T_{1/2}$
^{40}K	1.277×10^{9}
^{232}Th	1.405×10^{10}
^{235}U	7.038×10^{8}
^{238}U	4.468×10^{9}

The **specific heat capacity** of a substance is the quantity of heat required to change the temperature of unit mass of a substance by one unit.

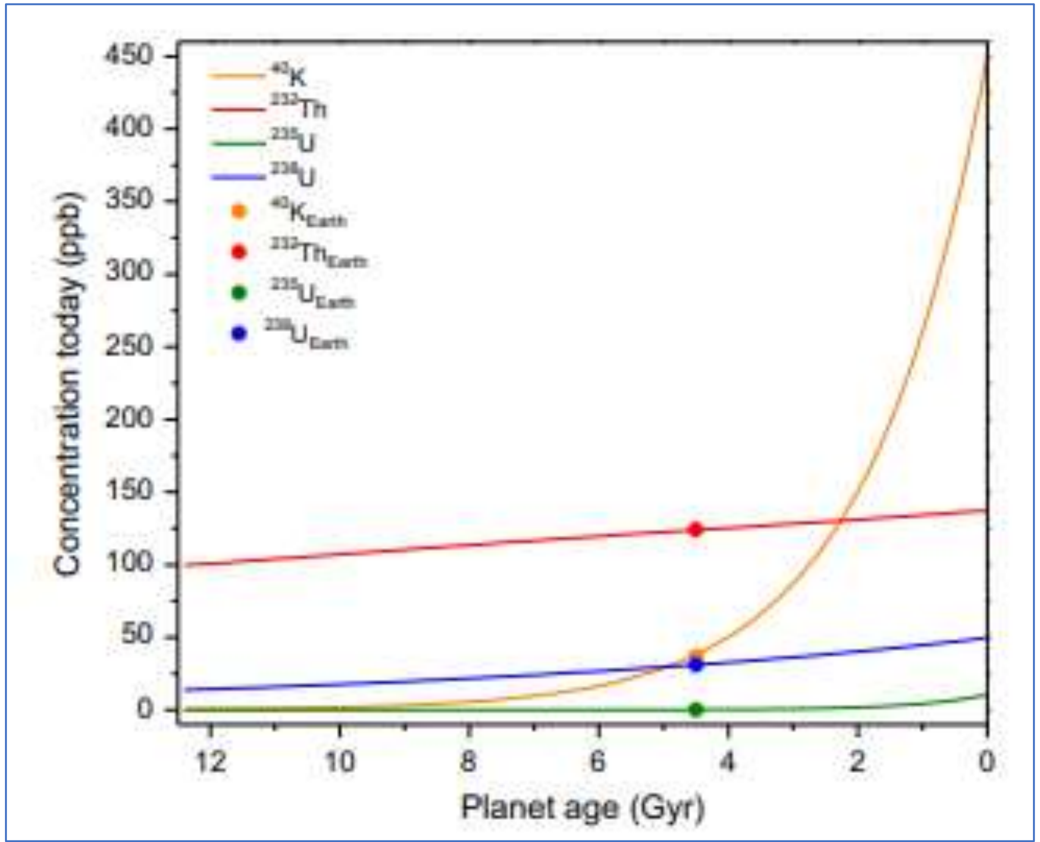
RADIOISOTOPES	SPECIFIC HEAT PRODUCED (W/Kg)
^{40}K	2.92×10^{-5}
^{232}Th	2.64×10^{-5}
^{235}U	5.69×10^{-4}
^{238}U	9.46×10^{-5}



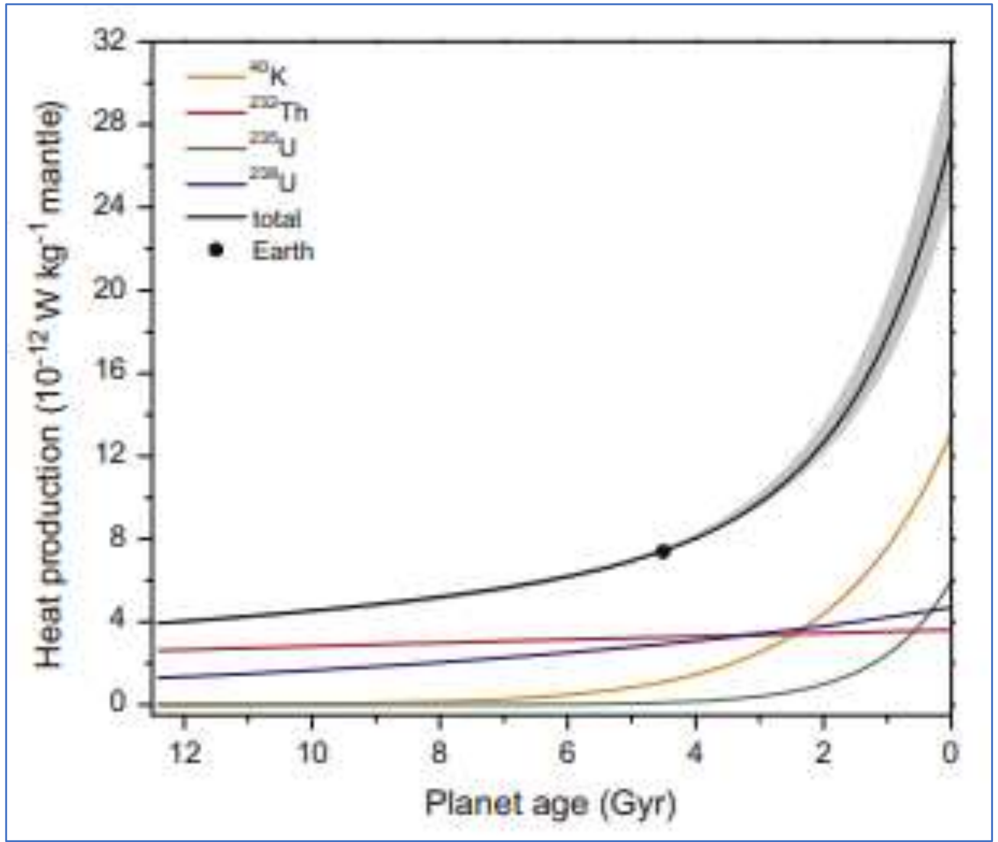


The figure above indicates the initial heat productions of ^{40}**K,** ^{232}**Th,** ^{235}**U,** ^{238}**U**, and their total in Cosmo-chemically Earth-like exoplanet mantles as a function of their formation time.

The figure above indicates the Heat production rates for the first 4.5 Gyr after exoplanets that formed 0, 4, 8, and 12.5 Gyr into galactic history.



The figure above indicates the concentrations of ^{40}K, ^{232}Th, ^{235}U, and ^{238}U in exoplanets today as a function of their age

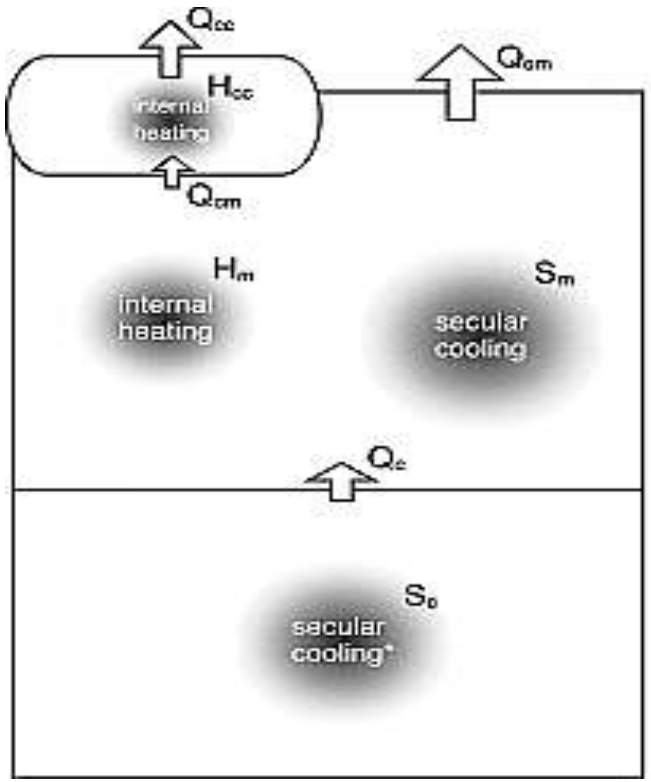


The figure above indicates the current heat production in exoplanets as a function of their age.

THE UREY RATIO

1. The Urey ratio is the ratio of internal heat production to surface heat flux.
2. The *bulk Earth* (BE) Urey ratio is the ratio of internal heat generation in the entire Earth to the total surface heat flux.
3. The convective Urey ratio is the ratio of internal heat generation in the mantle over the mantle heat flux.

- ❑ Qcc surface heat flux from continental regions
- ❑ Qom is surface heat flux from oceanic regions
- ❑ Qcm is heat flux from subcontinental mantle
- ❑ Hcc is the heat production of continental crust
- ❑ Hm is the heat production of the mantle
- ❑ Sm is heat flux due to the secular cooling of the mantle
- ❑ Sm is heat flux due to the secular cooling of the mantle
- ❑ Sc is heat flux due to the secular cooling of the core.



$Q_{cc} = Q_{cm} + H_{cc}$

$Q_{om} + Q_{cm} = H_m + S_m + Q_c$

$Q_c = S_c$

BE Ur $= (H_{cc} + H_m)/(Q_{om} + Q_{cc})$

convective Ur $= H_m/(Q_{om} + Q_{cm})$

IHR $= (Q_{om} + Q_{cm} - Q_c)/(Q_{cm} + Q_{om})$
$= (H_m + S_m)/(Q_{om} + Q_{cm})$

PRESENT-DAY THERMAL BUDGET	Value (TW)
Global heat flux	46
Oceanic heat flux	32
Continental heat flux	14
Bulk Silicate Earth heat production	16
Continental crust heat production	7.5
Depleted Mantle heat production	8.5
Convective heat flux	36.5
Convective Urey ratio	0.23
Secular cooling rate	124
Core heat flux	4.5
Internal heating ratio	0.87

THANK YOU