The Age of the Solar System

Age Dating

How old is the Solar System?
How old are its constuents?
In particular, how old is the Earth?

Related Questions

How have things changed or evolved since formation?
In Particular, how do planets evolve?
What is the evolutionary history of the Earth?
What is the history of Life on Earth?
(and what rôle does it play in the Earth's evoltion?)

Digression: The Importance of Time

Physical Processes (Chemical, Geological, Astrophysical, Cosmological)
Biological Processes (Formation, Growth, Ecological, Evolution)

The Age of the Earth

Theological Assertions

Hindu: 155 Tyr - 77.76 Tyr

Babylonian (~1200 BCE): 432,000 yr?

Jewish Calendar: 3760 BCE*

John Lightfoot (1602-1675): 3298 BCE

James Usher (1581-1656): 4004 BCE

Zoroastrian: 12,000 BCE

Historical Determinations (*e.g.,* genealogy)

Chinese Genealogies: <5000 BCE

Trojan War: 1194-1184 BCE (Eratosthenes)

also

Archaeology

***BCE: "Before the Current Era"**

Physical Determinations of Earth's Age

Sedimentation Rates

Thickness/Rate = 150 km/0.3 mm per year = 500 Myr

(Values from 3 Myr to 1.5 Gyr)

Salinity of the Seas

John Joly, 1899: 90 - 100 Myr

Cooling Times

Comte de Buffon,1779: 75,000 yr (by experiment)

Lord Kelvin, 1862: 98 Myr; 20 to 400 Myr

Age of the Sun

Hermann von Helmholtz,1854: 21 Myr

Simon Newcomb, 1884: 100 Myr

Biology

Evolution by Natural Selection requires > 400 Myr (Darwin)

Also Charles Lyell (1797-1875) estimates 240 MYr based on fossil mollusks.

Age Dating *via* Radioactive Decay

Radioactivity

Roentgen (1895) - X Rays
Bequerel (1896) - Radioactivity of Uranium
Marie Curie (1898) - Uranium, Polonium, Radium
("radio-active" and declining radioactivity)
Ernest Rutherford (1911) - Alpha particles and the atomic nucleus

Nomenclature

Atomic Structure

Chemistry and Atomic Physics
Nuclei and Electrons
Charges and Ions

Nuclear Structure

Nucleons = Protons & Neutrons
Atomic Number = Z = Proton Number
Atomic Weight = A = Nucleon Number
Isotopes: Varying A (*i.e.*, neutron number) at fixed Z
(Notation: C^{14}, U^{235}, U^{238}, *etc.*; but sometimes ^{14}C, ^{235}U, ^{238}U,..)

Nuclear Reactions

"Rules" for Nuclear Reactions

- Charge is conserved
- Nucleon number is conserved*
- Mass-energy is conserved

Example: **A <u>Fusion</u> Reaction**

$$H^1 + H^1 \rightarrow H^2 + e^+ + \nu$$

$$(p^+ + p^+ \rightarrow np^+ + e^+ + \nu)$$

Example: **A <u>Fission</u> Reaction**

$$U^{238} \rightarrow Th^{234} + He^4$$

$$(U^{238} \rightarrow Th^{234} + \alpha)$$

Example: **<u>Pair Production</u> and Particle-Antiparticle <u>Annihilation</u>**

$$e^- + e^+ \leftrightarrow \gamma$$

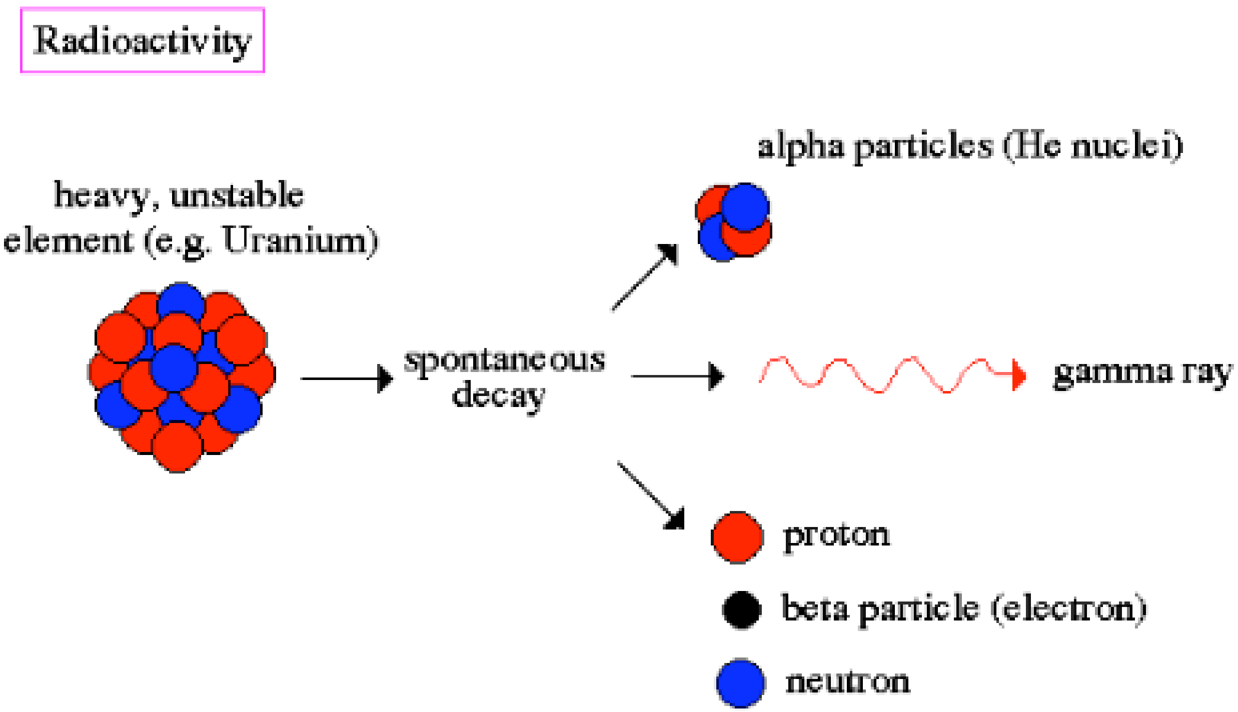
Note: Energy release (or consumption) from ΔMc^2

* excepting (unlikely) pair production or particle-antiparticle annihilation

Natural Radioactive Decay

Principal Decay Mechanisms

Alpha (α) Emission: a helium-4 nucleus (He^{++})
Beta (β) Emission: a positron (e^+) or electron (e^-)
Gamma (γ) Radiation: a high energy photon ("$h\nu$")



Natural Radioactive Decay

- Radioactive nuclei decay into other elements and isotopes.
- Each decay of a “parent” nucleus produces a “daughter” nucleus.
- The process ends when a stable non-radioactive nucleus is produced.

The rate of decays is proportional to the number of radioactive nuclei.

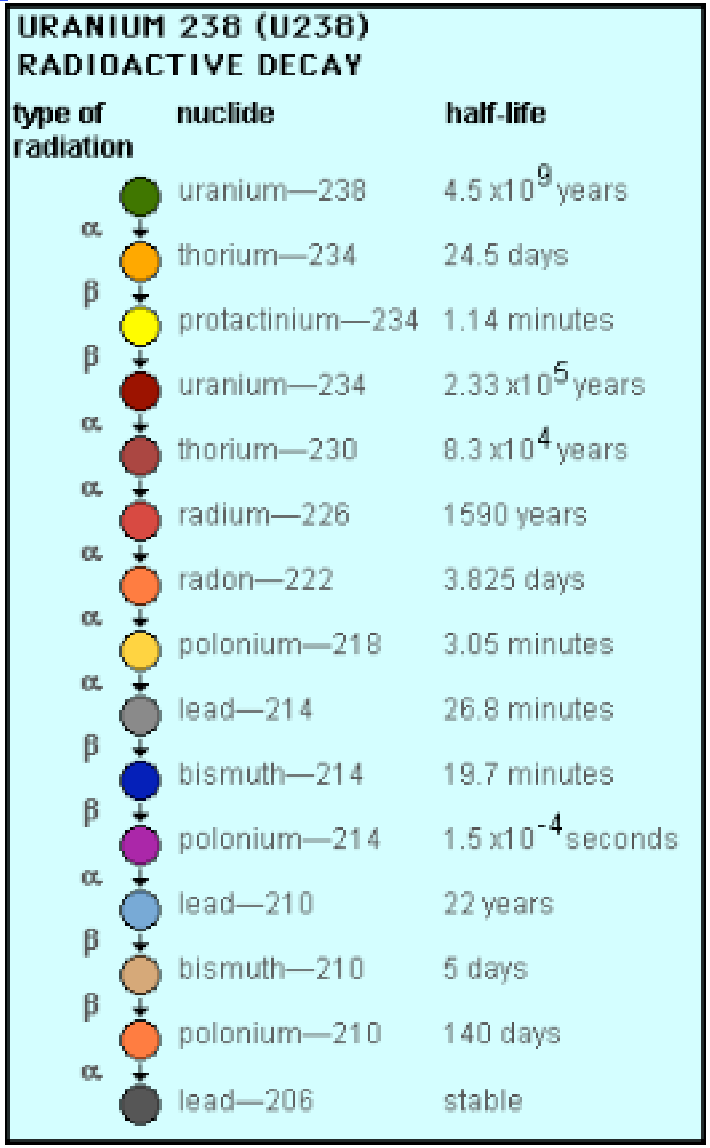
- Each decay step is characterized by a “half life”
- The number of radioactive nuclei is halved with the passage of each “half life”

Natural Radioactive Decay

After one half life, half of the parent atoms remain,
After two half lives, one-quarter remain,
After three half-lives, one-eighth remain, *etc.*

The total number of nuclei, radioacctive parent plus stable daughter, is a constant.

Radioactive decay proceeds until a stable isotope is reached



URANIUM 238 (U238)
RADIOACTIVE DECAY

type of radiation	nuclide	half-life
α	uranium—238	4.5 x10^{9} years
β	thorium—234	24.5 days
β	protactinium—234	1.14 minutes
α	uranium—234	2.33 x10^{5} years
α	thorium—230	8.3 x10^{4} years
α	radium—226	1590 years
α	radon—222	3.825 days
α	polonium—218	3.05 minutes
β	lead—214	26.8 minutes
β	bismuth—214	19.7 minutes
α	polonium—214	1.5 x10^{-4} seconds
β	lead—210	22 years
β	bismuth—210	5 days
α	polonium—210	140 days
	lead—206	stable

Natural Radioactive Decay

A Parent/Daughter ratio gives <u>time elapsed</u> since the sample was pure Parent

Important: This is generally the time elapsed since the sample solidified from melt. (Parent and Daughter elements generally separate upon melting.)

Cross-Checking: Major Radioactive Age Indicators

Decay Path......................Half Life

$Rb^{87} \rightarrow Sr^{87}$ .... 49.82 Gyr

$Re^{187} \rightarrow Os^{187}$ .... 42.97 Gyr

$Th^{232} \rightarrow Pb^{208}$ .... 13.89 Gyr

$U^{238} \rightarrow Pb^{206}$ .... 4.508 Gyr

$K^{40} \rightarrow Ar^{40}$ .... 1.277 Gyr

$U^{235} \rightarrow Pb^{207}$ .... 0.713 Gyr

also of interest:

$I^{129} \rightarrow Xe^{129}$ .... 15.7 Myr

$Hf^{182} \rightarrow W^{182}$ .... 9.0 Myr

$Pu^{244} \rightarrow Xe^{136}$ .... 80.8 Myr

and, particularly:

$C^{14} \rightarrow N^{14}$ .... 5,370 yr

The Age of the Earth

In Search of the oldest rocks:

Zircon ($ZrSO_4$) Grains (Australia) : 4.404 Gya*

(Melting Point 2200°C *versus* 1710°C for Silica and 1538°C for Iron)

Acasta Gneiss (Canada): 4.04 Gya

Akilia Island Greenstone (Greenland): 3.85 Gya
(Contains the earliest evidence for carbonaceous life)

Isua Supracrustal Rocks (Greenland): 3.75 Gya

•••••• The inferred age of the Earth is 4.567 Gyr •••••

Clarifications:

- **This dates the beginning of the accretion process**
- **Accretion is essentially complete by 4.47 Gya**
- **Solidification of the surface begins about 4.4 Gya**
  ....and is more-or-less complete by about 4.0 Gya

***Gya = "Gigayears ago"**

Ages of Solar System Objects

The Earth: 4.57 Gyr

Accretion complete by ~4.47 Gya
Note "Late Bombardment Era" ~3.9 Gya

Asteroids: 4.56 Gyr

Fragments obtained as Meteorites

The Moon: 4.51 Gyr

Samples from the Apollo Program
Meteoritic Fragments

Mars: 4.54 Gyr

Martian Meteorites

Sun: 4.57 Gyr

Models

Timeline: The Formation of the Earth

(13.7 Gya ------------ The Origin of the Universe)

4.57 ± 0.07 Gya ----------------- Formation of the Solar System

4.55 Gya --------------- First Solar System Solids (Meteorites)

4.533 Gya ----------------- Formation of the Moon (by collision)

4.53 Gya ---------------- Formation of Martian Crust (ALH84001)

4.527 Gya ------------------- Lunar Regolith (Apollo, Meteorites)

4.49 ± 0.04 Gya ----- Formation of the Sun Complete (ZAMS)

4.404 Gya --------------- First Terrestrial Solids (Zircon Grains)

4.04 Gya --- Oldest surviving rocks (Acasta Gneiss, Canada)

3.9± Gya --------------------- End of “Late Heavy Bombardment”

•

•

(3.85 Gya---- First Indicators of Carbonaceous Life)

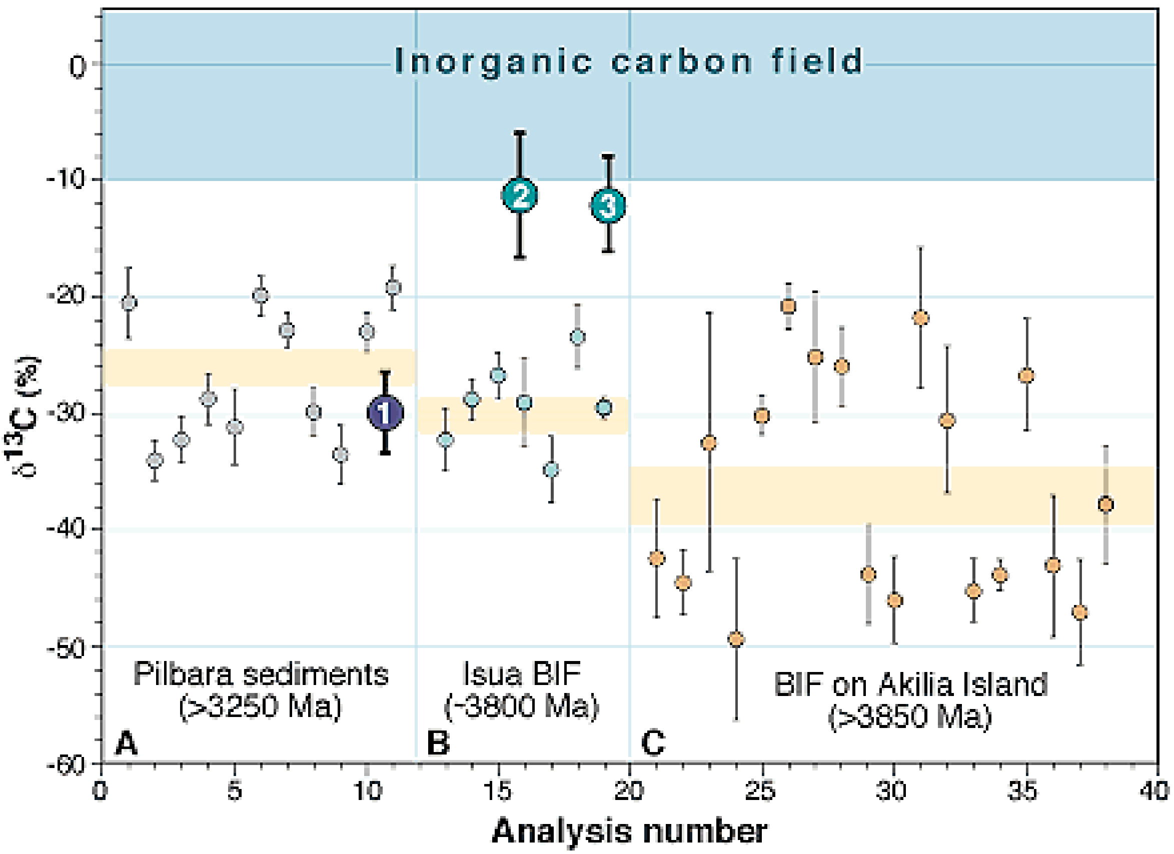
Timeline: Life on Earth

The C^{13}/C^{12} ratio as an indicator of life

Normal C^{13}/C^{12} abundance ratio is $R_o = 0.0112$

$$\delta C^{13} = 1000 \times (R - R_o)/R_o$$

A $\delta C^{13} < -10$ is considered a robust indicator of life



Timeline: Life on Earth

(···· 85 % of the History of Life on Earth ····)

3.85 Gya---------------- First Indicators of Carbonaceous Life (δC^{13})

3.5 Gya ----------- Anaerobic Photosynthesis (O_2 production, LCE?)

3.465 Gya ------------- Oldest Fossils (Microbial Filaments, Australia)

3.4 Gya -------- Banded Iron Formations (Sedimentation, oxidation)

3.375 Gya ------------------------------- Fossil prokaryotes (South Africa)

3.0 Gya ------------ Colonial Cyanobacteria (Stromatolites, Australia)

2.4 Gya ---------------- The “Great Oxidation” (~O.01 PAL, PAL = 23%)

2.1 Gya ------------------------------ The First Eukaryotes (Algal Ribbons)

1.2 Gya-------------------------------- Cell Division (Sex!), Multicellular Life

600 Mya -- Multicellular Animals

542 -530 Mya ----- The “Cambrian Explosion” (Body plans and parts)

The Early Fossil History

Microscopic Fossil Prokaryotes (3.375 Gya)
Non-Nucleated Cells: Archaea & Bacteria
Anaerobic Photosynthesis

•**Fossil Mats (Stomatolites)** (3.0 Gya)
Colonial Cyanobacteria
Aerobic Photosynthesis

• **Fossil Algae** (2.1 Gya)
(Nucleated Cells: Eukaryotes)

• **Multicelluar Fossils (Sponges)** (0.60 Gya)

• **Complex Animals (and tracks on land)** (0.53 Gya)
"The Cambrian Explosion"

• **Primates** (0.060 Gya) and ***Homo Erectus*** (0.001 Gya)
Extinction of the Dinosaurs at 0.065 Gya

Biochemistry and the Earth's Atmosphere

• **First Chemical Indicators:** δC^{13} (3.85 Gya)
Atmospheric Constituents : CO_2, CO, N_2, H_2O, $H_2\uparrow$ (Note: No O_2 or O_3)

• **Slow Oxygenation** (3.85 to 2.33 Gya)
••• Oxygen increases from 10^{-12} to 10^{-5} PAL (PAL = 23%) •••

Anaerobic Decomposition: $CO_2 + 2H_2O \rightarrow CH_4 + 2O_2$
Anoxic Photosynthesis: $CO_2 + 2H_2O + h\nu \rightarrow CH_4 + 2O_2$
Oxygenic Photosynthesis: $CO_2 + H_2O + h\nu \rightarrow CH_2O + O_2$
also
Anoxic Fermentation & Methanogenesis: $2CH_2O \rightarrow CH_3COOH \rightarrow CH_4 + CO_2$
but
Methane Eaters: $CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$
Iron Oxidation (Basalt): $Fe + H_2O \rightarrow FeO + H_2\uparrow$
and (Magnetite): $3FeO + H_2O \rightarrow Fe_3O_4 + H_2\uparrow$

• **The Great Oxygenation** (2.33 Gya)
••• Oxygen increases from 10^{-5} to 10^{-2} PAL •••
Extinction by Oxygen Poisoning
Ozone Formation $3O_2 + h\nu \rightarrow 2O_3$