The Age of the Solar System

Age Dating

How old is the Solar System?
How old are its constituents?
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 evolution?)

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 14C, 235U, 238U,..)
Nuclear Reactions

“Rules” for Nuclear Reactions

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

Example: A Fusion Reaction
\[ \text{H}^1 + \text{H}^1 \rightarrow \text{H}^2 + e^+ + \nu \]
\[ (p^+ + p^+ \rightarrow np^+ + e^+ + \nu) \]

Example: A Fission Reaction
\[ \text{U}^{238} \rightarrow \text{Th}^{234} + \text{He}^4 \]
\[ (\text{U}^{238} \rightarrow \text{Th}^{234} + \alpha) \]

Example: Pair Production and Particle-Antiparticle Annihilation
\[ e^- + e^+ \leftrightarrow \gamma \]

Note: Energy release (or consumption) from \( \Delta Mc^2 \)

* 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 ("hν")
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, radioactive parent plus stable daughter, is a constant.
Radioactive decay proceeds until a stable isotope is reached.

<table>
<thead>
<tr>
<th>Type of Radiation</th>
<th>Nuclide</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>uranium—238</td>
<td>$4.5 \times 10^9$ years</td>
</tr>
<tr>
<td>β</td>
<td>thorium—234</td>
<td>24.5 days</td>
</tr>
<tr>
<td>β</td>
<td>protactinium—234</td>
<td>1.14 minutes</td>
</tr>
<tr>
<td>α</td>
<td>uranium—234</td>
<td>$2.33 \times 10^5$ years</td>
</tr>
<tr>
<td>α</td>
<td>thorium—230</td>
<td>8.3 $\times 10^4$ years</td>
</tr>
<tr>
<td>α</td>
<td>radium—226</td>
<td>1590 years</td>
</tr>
<tr>
<td>α</td>
<td>radon—222</td>
<td>3.825 days</td>
</tr>
<tr>
<td>α</td>
<td>polonium—218</td>
<td>3.05 minutes</td>
</tr>
<tr>
<td>α</td>
<td>lead—214</td>
<td>26.8 minutes</td>
</tr>
<tr>
<td>β</td>
<td>bismuth—214</td>
<td>19.7 minutes</td>
</tr>
<tr>
<td>β</td>
<td>polonium—214</td>
<td>$1.5 \times 10^{-4}$ seconds</td>
</tr>
<tr>
<td>α</td>
<td>lead—210</td>
<td>22 years</td>
</tr>
<tr>
<td>β</td>
<td>bismuth—210</td>
<td>5 days</td>
</tr>
<tr>
<td>β</td>
<td>polonium—210</td>
<td>140 days</td>
</tr>
<tr>
<td>α</td>
<td>lead—206</td>
<td>stable</td>
</tr>
</tbody>
</table>
Natural Radioactive Decay

A Parent/Daughter ratio gives time elapsed 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

<table>
<thead>
<tr>
<th>Decay Path</th>
<th>Half Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rb(^{87}) → Sr(^{87})</td>
<td>49.82 Gyr</td>
</tr>
<tr>
<td>Re(^{187}) → Os(^{187})</td>
<td>42.97 Gyr</td>
</tr>
<tr>
<td>Th(^{232}) → Pb(^{208})</td>
<td>13.89 Gyr</td>
</tr>
<tr>
<td>U(^{238}) → Pb(^{206})</td>
<td>4.508 Gyr</td>
</tr>
<tr>
<td>K(^{40}) → Ar(^{40})</td>
<td>1.277 Gyr</td>
</tr>
<tr>
<td>U(^{235}) → Pb(^{207})</td>
<td>0.713 Gyr</td>
</tr>
<tr>
<td>I(^{129}) → Xe(^{129})</td>
<td>15.7 Myr</td>
</tr>
<tr>
<td>Hf(^{182}) → W(^{182})</td>
<td>9.0 Myr</td>
</tr>
<tr>
<td>Pu(^{244}) → Xe(^{136})</td>
<td>80.8 Myr</td>
</tr>
<tr>
<td>C(^{14}) → N(^{14})</td>
<td>5,370 yr</td>
</tr>
</tbody>
</table>

also of interest:

Also, particularly:

and, particularly:
The Age of the Earth

In Search of the oldest rocks:

Zircon (ZrSO₄) 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)
The $^{13}\text{C}/^{12}\text{C}$ ratio as an indicator of life
Normal $^{13}\text{C}/^{12}\text{C}$ abundance ratio is $R_0 = 0.0112$

$$\delta^{13}\text{C} = 1000 \times \frac{(R - R_0)}{R_0}$$

A $\delta^{13}\text{C} < -10$ 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 (δC¹³ )
3.5 Gya --------- Anaerobic Photosynthesis (O₂ 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” (~0.01 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)

• Multicellular 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**: $\delta^{13}C$ (3.85 Gya)
  Atmospheric Constituents: CO$_2$, CO, N$_2$, H$_2$O, H$_2$↑ (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: $\text{CO}_2 + 2\text{H}_2\text{O} \rightarrow \text{CH}_4 + 2\text{O}_2$
  - Anoxic Photosynthesis: $\text{CO}_2 + 2\text{H}_2\text{O} + h\nu \rightarrow \text{CH}_4 + 2\text{O}_2$
  - Oxygenic Photosynthesis: $\text{CO}_2 + \text{H}_2\text{O} + h\nu \rightarrow \text{CH}_2\text{O} + \text{O}_2$
    - Also
  - Anoxic Fermentation & Methanogenesis: $2\text{CH}_2\text{O} \rightarrow \text{CH}_3\text{COOH} \rightarrow \text{CH}_4 + \text{CO}_2$
    - But
  - Methane Eaters: $\text{CH}_4 + 2\text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{CO}_2$
  - Iron Oxidation (Basalt): $\text{Fe} + \text{H}_2\text{O} \rightarrow \text{FeO} + \text{H}_2$↑
  - and (Magnetite): $3\text{FeO} + \text{H}_2\text{O} \rightarrow \text{Fe}_3\text{O}_4 + \text{H}_2$↑

- **The Great Oxygenation** (2.33 Gya)
  - Oxygen increases from $10^{-5}$ to $10^{-2}$ PAL
  - Extinction by Oxygen Poisoning
  - Ozone Formation: $3\text{O}_2 + h\nu \rightarrow 2\text{O}_3$