Origin of the Solar System

Meteorites

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What you can learn from meteorites about:
- Big Bang cosmology
- Galactic evolution
- Stellar evolution
- Origin and evolution of the Solar System
- Origin of life
(not necessarily in that order!)
Techniques

- **Microscopy**
  - Optical (texture)
  - Electron (composition)
  - X-ray diffraction (structure)

- **Mass spectrometry**
  - Radiogenic isotope
  - Stable isotope
  - Organic
Star Formation Cycle

Molecular Cloud

Interstellar Dust
Inorganic
Organic

Supernova

Star formation & evolution
Molecular Cloud

Protoplanetary Disk

Planet Formation

Meteorites

Comets

Planets

KBO

Satellites

Rings

Asteroids
Meteorites come from Asteroids

- Asteroids are minor planets that orbit the Sun
- A planet that never got built, not a planet that exploded

- Asteroid (433) Eros:
  - S-class asteroid
  - 33 x 13 x 13 km
  - 21 x 8 x 8 miles

Credit: NASA/Goddard Space Flight Center
Types of Meteorite

• Original classification:
  - Irons (made of iron)
  - Stones (made of stone)
  - Stony-Irons (mixture of stone and iron)

• More recent classification:
  - Melted (irons; stony-irons; achondrites)
  - Unmelted (chondrites)
Unmelted Stone Meteorites

- Chondrites
- The original dust from which the Solar System formed
- From asteroids that got warm, but never completely melted
- Made of chondrules:
  - small droplets of quenched silicates
- Other components:
  - CAIs, metal, sulphides, organics, matrix
Chondrules

Spherical Fe, Mg silicate grains formed by flash heating
CAIs

Calcium- and Aluminium-rich Inclusions

2 mm
Melted Metal-rich Meteorites

- Iron, with some nickel (±silicates)
- Characterised by Widmanstatten pattern
  - Intergrowth of kamacite (< 5% Ni) and taenite (> 7% Ni)
- Same process that makes steel from iron ore
- Same process that produced the Earth's core and core-mantle boundary
Melted Stone Meteorites

Achondrites: earliest basalts
Radiogenic Isotopes

- Parent (P) decays to Daughter (D) with a characteristic half-life.
- Pb-Pb system (using relationships between 204, 206 and 207 isotopes) gives an absolute age.
- Fractionation (e.g., during melting) separates P from D.
- Can determine age intervals relative to Pb-Pb age.
- Different isotope systems date different processes.
# Radionuclide Half Lives

<table>
<thead>
<tr>
<th>Parent</th>
<th>Daughter</th>
<th>Half Life (Gyr)</th>
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<tbody>
<tr>
<td>$^{147}$Sm</td>
<td>$^{143}$Nd</td>
<td>106</td>
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<tr>
<td>$^{87}$Rb</td>
<td>$^{87}$Sr</td>
<td>48.8</td>
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<tr>
<td>$^{238}$U</td>
<td>$^{206}$Pb</td>
<td>4.45</td>
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<tr>
<td>$^{40}$K</td>
<td>$^{40}$Ar</td>
<td>1.25</td>
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<tr>
<td>$^{235}$U</td>
<td>$^{207}$Pb</td>
<td>0.70</td>
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</table>

<table>
<thead>
<tr>
<th>Parent</th>
<th>Daughter</th>
<th>Half Life (Myr)</th>
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</thead>
<tbody>
<tr>
<td>$^{41}$Ca</td>
<td>$^{41}$K</td>
<td>0.15</td>
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<tr>
<td>$^{26}$Al</td>
<td>$^{26}$Mg</td>
<td>0.73</td>
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<tr>
<td>$^{10}$Be</td>
<td>$^{10}$B</td>
<td>1.5</td>
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<tr>
<td>$^{60}$Fe</td>
<td>$^{60}$Ni</td>
<td>1.5</td>
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<tr>
<td>$^{53}$Mn</td>
<td>$^{53}$Cr</td>
<td>3.7</td>
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<tr>
<td>$^{107}$Pd</td>
<td>$^{107}$Ag</td>
<td>6.5</td>
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<tr>
<td>$^{182}$Hf</td>
<td>$^{182}$W</td>
<td>9</td>
</tr>
<tr>
<td>$^{129}$I</td>
<td>$^{129}$Xe</td>
<td>16</td>
</tr>
</tbody>
</table>
Planetary Evolution

- Use radiouclides with intermediate half-lives (1-10 Myr)
- Timescales of core formation
  - Iron and stony-iron meteorites
  - Hf-W; Pd-Ag
- Timescales of crustal melting
  - Achondrites
  - Mn-Cr
Nebula Evolution

- Use short-lived radionuclides ($T_{1/2} < 1$ Myr)
  - $^{26}$Al, $^{41}$Ca, $^{60}$Fe
- Produced by high neutron flux (supernova?)
- Presence of daughter isotopes implies short timescale between production of radioisotope and incorporation into solid material
- Traditional view allows this to define a chronology: CAIs predate chondrules by $\sim 1$ Ma
Timescales
X-Wind model

• Spatial, rather than temporal relationship between components
• CAIs, chondrules formed close to young sun, then thrown outwards on jets
• Major challenge to distinguish between nebula and X-wind models
• $^{10}$B isotopes from decay of $^{10}$Be $T_{1/2} \approx 1.5$ Myr
• $^7$Li isotopes from decay of $^7$Be $T_{1/2} \approx 52$ days

• Shu et al. (1997)
Presolar Grains

- Minor constituent of chondrites
- Recognised on basis of unusual stable isotope compositions
- Inorganic
  - Graphite; diamond; SiC; corundum ($\text{Al}_2\text{O}_3$)
  - Noble gases (Xe, Ne); $^{13}\text{C}/^{12}\text{C};^{15}\text{N}/^{14}\text{N}$
- Organic
  - Aliphatic
  - Aromatic
  - D/H; $^{13}\text{C}/^{12}\text{C};^{15}\text{N}/^{14}\text{N}$
- Interstellar, circumstellar, supernovae
Nanodiamonds

- Approx 3 nm in size
- Not produced in a single stellar source
- Possibly produced in outflow from supernova
Inorganic Interstellar Grains
Organic Interstellar Material

- Occurs as a variety of species
  - Aliphatic (straight and branched chain)
  - Aromatic
- Enriched in D, $^{13}\text{C}$ and $^{15}\text{N}$
- Tracer for ion-molecule reactions on grains in the ISM
  - Astrochemistry
- Evolution of molecular clouds
Circumstellar Grains
Sources of Presolar Grains

- **Diamond**: 2 nm
  - Xe-HL
  - SN

- **Mainstream SiC**: 0.3-20 μm
  - Xe-S, Ne-E(H)
  - AGB stars

- **Graphite**: 1-20 μm
  - Ne-E(L)
  - SN, AGB stars, Novae

- **SiC type X**: 1-5 μm
  - SN

- **Corundum**: 0.5-3 μm
  - RG stars, AGB stars

- **Si₃N₄**: ~1 μm
  - SN

**Bulk abundances in primitive meteorites**
Stellar and Galactic Evolution

- Presence of different presolar grains, from a variety of environments

- Possibility of dating grains
  - Different generations of grains
  - Chemical evolution of galaxy?
Big Bang Cosmology

• Information from D/H
• D created in BB
  - Destroyed in stars
  - Tracer for physical and chemical processes
  - Allows refinement of baryon/photon ratio
Meteorites from the Moon?
Meteorites from Mars?
They must be from Mars!

They contain martian atmosphere trapped during a shock event.
Evolutionary Timescales

- Big Bang cosmology (D/H ratio)
- Galactic evolution (circumstellar grains)
- Molecular cloud evolution (organic molecules)
- Stellar evolution (interstellar grains)
- Nebula (CAIs, chondrules)
- Planetary melting (achondrites)
- Moon formation (lunar samples)
- Martian processes (martian meteorites)
Origin of Life

- Comets and asteroids carry water and organic molecules
- The building blocks of life
- Early bombardment of Earth
  - Impact frustration of life
- Bombardment decreased
  - Water and organics added
Planetary Science 2

Life Beyond Earth?
How is Life defined?

• Growth, reproduction, locomotion, response, excretion, respiration, nutrition
  - Non-living entities (e.g., fire)
  - Virus?

• The ability to adapt and evolve
  - Heredity: transfer of information
Conditions for life to arise

Starting assumptions
- laws of physics and chemistry not violated
- Carbon-based

Starting materials
- building blocks (CO, CH₄, NH₃, H₂O {S,P})
  - Role of comets
- substrate
- energy
The Role of Comets

- Dominantly ice
- Rich in organic compounds
- Major contributor to planetary bombardment
  - Delivered water and organics to all planets
  - Potential for life throughout Solar System
  - Not panspermia
Conditions for Life

- Building blocks (the role of comets)
- Substrate, energy, time, stability
Stages in the Origin of Life

- Simple molecules (CO, CH$_4$, NH$_3$)
- Complex molecules (RNA)
- Template for self-replication
- Membrane/boundary layer
What evidence should we look for?

- Legs, wings, fins, fur, flowers, roots?
- Something less complex?
  - Microorganisms (bacteria, archaea)
- Habitable niches
  - Liquid water
    - Temperature: -10°C to +115°C
    - pH: 0.7 - 10
    - Salinity: 37% NaCl
  - u.v. radiation
  - Pressure
  - Nutrient supply/energy
Habitable Niches on Earth

• Moderate environments
  - All phyla

• Extreme environments
  - Mainly microorganisms
    • deep crustal rocks
    • thermal springs
    • ocean floor (hydrothermal vents)
    • Antarctica
Antarctica
cryptoendolithic bacteria
Mars

- Source of heat
- Liquid water
- Atmosphere
Life on Mars?
Ancient fossil life on Earth?

‘Microfossils’ in the Apex Chert, Western Australia (Schopf, 1983)

Recent work has re-interpreted these structures as non-biological (Brasier group, Oxford)
Ocean floor

hydrothermal vent fauna
Europa

- heated by tidal heating
- little topography
- crust of water ice underlain by slush/rock
Titan

- Largest satellite of Saturn
- Very thick atmosphere (N$_2$, CH$_4$)
- Surface oceans (NH$_3$, CH$_4$, C$_2$H$_6$, )
- Surface temp. -200°C

 horizon at 88.5°
Life Beyond the Solar System?

• Extra-solar planets
  - ~ 120 found so far
  - Mostly ‘hot Jupiters’

• Search for Earth-like planets orbiting solar-type stars
  - Darwin/TPF missions
   • What will they look for?
Would Earth have been recognised as a potential host of life ~ 2 byr ago?
Evolution

Selection in a competitive environment

• Starting point
  - Physics, chemistry, ingredients

• Environmental stress
  - Atmosphere
  - Magnetic field
  - Tectonic structure

• Chance
  - Asteroid impact

Lead to different evolutionary pathways
Different Evolutionary Pathways?

Earth is special
Summary

- Have we found evidence for extant life beyond Earth?
  - No
- Have we found evidence for extinct life beyond Earth?
  - No
- Have we found evidence for habitats where life might exist beyond Earth?
  - Yes