The Starting Materials
Part I: The Origins of the Elements

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The Starting Materials
Part I: The Origins of the Elements

- Big Bang nucleosynthesis
- Nucleosynthesis in stars
  - Key nucleosynthesis processes
  - Stellar evolution related to nucleosynthetic processes
- Presolar grains (stardust) in meteorites and cosmic dust
  - Stellar sources
  - Probes of specific nuclear reactions
  - Stardust mineralogy – their Galactic history
Big Bang Nucleosynthesis

The First Atoms

- Almost all fundamental particles (protons, electrons, neutrons) originated within the first few seconds

- ~1 minute later the Universe cooled to <10⁹ Kelvin, allowing atomic nuclei to form

- All of the Hydrogen, and most of the Helium and Lithium in the Universe formed within the first minute.

- NO heavy elements formed in the Big Bang that permeates the Universe

The light from these galaxies reached us after traveling for 13 billion years. Thus, we see ‘young’ galaxies formed within 1 billion years of “the Beginning”
H and He are by far most abundant elements
Li, Be and B are anomalously low in abundance
Exponential drop in abundance with increasing Z
Even Z > odd Z
Fe and neighbors are anomalously abundant
These two papers first explained nuclear reactions in stars responsible for the production of the elements.
Energy Generation in Stars

The Sun's energy comes from the fusion of H into He

Energy can be created from mass!

The mass of a nucleus is less than the sum of the masses of the protons and neutrons that it is made from!

\[
e = mc^2
\]

<table>
<thead>
<tr>
<th>Protons</th>
<th>Neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass = 2 × 1.00728 u</td>
<td>mass = 2 × 1.00866 u</td>
</tr>
<tr>
<td>mass of 2p + 2n = 4.03188 u</td>
<td>mass = 4.00153 u</td>
</tr>
</tbody>
</table>

\[ \Delta m = 0.03035 \text{ u} = 5 \times 10^{-26} \text{ g} \]
\[ E = \Delta mc^2 = 28.3 \text{ MeV} \]

nuclear binding energy
Fusion of H into He

Reaction timescales

- $10^9$ years
- 1 second
- $10^6$ years
Nuclear binding force is strong but very short range

Nuclei must overcome Coulomb repulsive force to fuse together

Potential diagram for nuclear collisions

Coulomb barrier
Charge repulsive force

Temperature ~ $15 \times 10^6$ K
$E = kT \sim 1$ keV
However!

$p + p$ barrier $E = 550$ keV

The sun is not hot enough for fusion ?!
Quantum Tunneling

in classical physics, kinetic energy must be higher than the potential to pass the barrier

Quantum mechanics "uncertainty principle" enables 'tunneling' through barriers if the potential is lower on the other side!

Probability of penetrating barrier $\sim \exp[-(E_{\text{barrier}}/E_{\text{thermal}})^{1/2}]$

Fusion reaction rates increase exponentially with Temperature

For $p + p$ reaction in the Sun, Probability $= 10^{-22}$!

This is why the Sun will live for 10 billion years
Isotope with excess neutrons
\[ n \rightarrow p + e^- \]

Neutron capture reactions are *easy*!
- No charge barrier
- Can occur even at room temperature

S process is slow addition of neutrons compared with radioactive decay

S process is the most important source of many elements > Fe

This occurs at the late stages of a stars life
Core Temperatures in Stars

Stars are balanced in gravitational/thermal equilibrium
- Thermal pressure in core maintained by fusion reactions
- Evolution and lifetime of a star is “easy to predict”

Pressure forces balance gravity force (hydrostatic equilibrium)
- $F_{\text{gravity}} = P_{\text{gas}} + P_{\text{radiation}}$
- $\frac{mGM}{R^2} = r_kT + sT^4$

The temperature of the core is proportional to the mass of the star

High mass stars have short lives
- Higher thermal pressure required to support higher mass
- Fusion rates increase exponentially with temperature
Stellar Evolution
Main sequence star

H, He core

- H in the core is gradually converted into He
- H in the core is eventually completely converted into He
- This is the longest lasting stage of a star’s life
  - 10 million – 100 billion years, depending on stellar mass
Stellar Evolution

Red giant star

- Without H fusion, the He core cannot thermally support itself – the He core contracts
- Pressure, temperature increase in the core
- H burning starts on a shell around the core
- With higher core T, the star EXPANDS
Red Giant Stars

**THE SUN IN 5 BILLION YEARS**

About the size of the Earth’s orbit!

- Diameter ~ 300 million km
- Core diameter ~ 10,000 km
- Core temperature 100 million K
- Star luminosity 1,000 x the Sun
Stellar Evolution

Red giant star

- H burning shell
- He burning core

- He core mass continues to increase
- He core continues to contract, raising T even more
- Eventually T is high enough for Helium fusion reactions

The Triple Alpha Process (Helium Fusion)

\[ ^4\text{He} + ^4\text{He} + ^4\text{He} \rightarrow ^{12}\text{C} + ^{3}\text{He} \]

(alpha particle)
Stellar Evolution

AGB star transition

- He core is converted from He into C,O
- The star is now an "AGB star"
- He burns in a shell around the core
- S process elements made in He shell
- H burns in a shell around the He shell

Primary neutron source

$^{13}\text{C} + ^{4}\text{He} \rightarrow ^{16}\text{O} + \text{n}$
- He shell gains mass from H fusion shell above
- He shell contracts and briefly burns strongly (flash)
- He flash creates a strong thermal pulse, ejecting some material into space
- He shell thermal pulses can occur many times

- He shell mixes with convective envelope
- C made from He burning makes the surface C-rich (carbon star)
- Thermal pulses eject stellar material into space
- The entire envelope is ejected, making a planetary nebula
Planetary Nebula

The fate of the Sun

Luminous gas and dust cloud expelled from AGB star
Central remnant is a white dwarf

Helix planetary nebula, Hubble telescope
Stellar Evolution
Massive Stars

High mass stars have core T high enough to ignite C,O fusion

Fusion of heavier elements continues at increasingly higher T, reaching $3 \times 10^9$ K for Si fusion

Fusion ends with Fe, which has the highest binding energy
Supernovae

Stand back!

Fusion beyond Fe sucks energy from the star

Star collapses and then explodes

Explosion 100 billion times brighter than the sun
Explosive Nucleosynthesis

R Process

$10^{12}$ times greater neutron density compared with s process

Very short-lived isotopes may capture a neutron before decaying

s process, r process have different products
Nucleosynthesis Summary

- All H and most He formed in the Big Bang
- He and all other elements form in stars
- Fusion reactions produce most elements up to Fe
- Heavy elements mostly made by s process and r process
Stars form from the remnants of previous generations of many other stars.

Most stardust resides in the Galaxy for a long time ($10^8$ years).

In large star forming regions such as Orion (shown), massive stars may evolve and die (supernovae) while others are still forming.
The Solar System was built from stardust

Almost everything has since been destroyed and mixed together

The Solar System now has a very uniform isotopic composition

Presolar grains (stardust) can be identified by their unusual isotopic ratios
Stardust in Meteorites

Murchison meteorite: well preserved sample of early Solar System

Noble gas with exotic isotopic compositions found in meteorites. Finding the carriers was tricky.

Noble gas carriers found by dissolving 99.9% of the meteorite in acid.

Noble gas carriers survived!

Discovery team: Ed Anders, Ernst Zinner, Roy Lewis, Sachiko Amari.

Figure 1. Exotic noble gas components present in presolar carbonaceous grains. Diamond is the carrier of Xe-HL, SiC the carrier of Xe-S and Ne E(H), and graphite the carrier of Ne E(L) (source: Anders and Zinner (1993)).
Stardust Extracted from Meteorites

- SiC
- Si₃N₄
- Graphite
- Nanodiamonds
- Al₂O₃
- Hibonite
- Spinel
- Olivine
- Amorphous silicate

Typical size: 1 μm
Abundance: 1 – 100 ppm
Dust condensation in O-rich stellar outflows

<table>
<thead>
<tr>
<th>T</th>
<th>Phase</th>
<th>Equilibrium thermodynamics (solar gas, 10^{-5} bars, after Yoneda &amp; Grossman 1995; Ebel MESS-2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1633</td>
<td>Corundum</td>
<td>Identified as presolar grains</td>
</tr>
<tr>
<td>1562</td>
<td>Hibonite</td>
<td>No silicate stardust “rocks” found yet</td>
</tr>
<tr>
<td>1537</td>
<td>Perovskite</td>
<td></td>
</tr>
<tr>
<td>1472</td>
<td>Melilite</td>
<td></td>
</tr>
<tr>
<td>1351</td>
<td>Spinel</td>
<td></td>
</tr>
<tr>
<td>1320</td>
<td>Plagioclase</td>
<td></td>
</tr>
<tr>
<td>1305</td>
<td>Forsterite</td>
<td></td>
</tr>
<tr>
<td>1287</td>
<td>Metal (Fe+Ni,Co,Cr,Si)</td>
<td></td>
</tr>
<tr>
<td>1250</td>
<td>Titanium Oxide</td>
<td></td>
</tr>
<tr>
<td>1246</td>
<td>Enstatite</td>
<td></td>
</tr>
<tr>
<td>1200</td>
<td>Cr-spinel (MgAl_{2}O_{4}-MgCr_{2}O_{4})</td>
<td></td>
</tr>
<tr>
<td>&lt;1000</td>
<td>FeO</td>
<td></td>
</tr>
</tbody>
</table>

Figure courtesy L. Nittler

Nittler, Alexander, Stadermann, Zinner (2005) MPS 40, 5208
Nittler, Alexander, Stadermann, Zinner (2005) LPS 36, 2200
Isotopic Signatures of Stardust

Major and minor element isotopic ratios vary by a factor of 10,000

Isotopic compositions reflect distinct nucleosynthetic processes

Identify stellar source, age, metallicity

Figure courtesy E. Zinner
S-Process Signatures in SiC
Product of AGB stars

Bulk measurement

Anomalous Xe found in meteorite acid residues led to the chemical isolation of SiC and nanodiamonds

Savina et al. (2002) GCA
**Short-Lived Nuclides from Supernovae**

- $^{44}\text{Ca}$ and $^{49}\text{Ti}$ enrichments observed in rare SiC grains

- Grain must have formed shortly after nucleosynthetic production
  - Requires stellar source

- Resist loss or isotopic exchange since then (>4.5 billion years)

- Identify extinct nuclides by isotopic anomaly in daughter product

**Example: $^{44}\text{Ti}$**

- produced only in supernovae
- $t_{1/2} = 60$ years
- $^{44}\text{Ti} \rightarrow ^{44}\text{Ca}$
- $^{44}\text{Ca}/^{42}\text{Ca}$ ratios reach 5,000 x solar in stardust

**Example: $^{49}\text{V}$**

- $t_{1/2} = 331$ days
- $^{49}\text{V} \rightarrow ^{49}\text{Ti}$
- Grains condensed within a few years of nucleosynthesis

Silicate and Oxide Stardust

- >100 presolar silicates and oxides found so far
- ~99% originate from RG/AGB
- Supernova dust is rare (~1%)
- Galactic chemical evolution
- Estimate for age of the Galaxy

Floss & Stadermann (2005)
Huss et al. (1993)
Messenger et al. (2003) Science
Nagashima et al. (2004) Nature
Supernova Dust Formation

Supernova olivine grain

Olivine: \((\text{Mg,Fe})_2\text{SiO}_4\)

- \(^{18}\text{O}/^{16}\text{O} = 13 \times \text{solar}\)
- \(^{17}\text{O}/^{16}\text{O} = 1/3 \times \text{solar}\)
- \(^{29}\text{Si}/^{28}\text{Si} = 0.8 \times \text{solar}\)

\(^{18}\text{O}\)-enrichment in high C/O zone

A 500 nm grain can tell us how stars explode!

Model requires mixing of inner material with outer layers without contribution from intervening zones.

Figure courtesy L. Nittler

Messenger et al. (2005) Science
See also supernova SiC & graphite: Nittler et al. 1996, Hoppe et al. 2000
Theoretical and Observational Evidence for Complex Mixing in Supernovae

*Chandra* x-ray image of Cassiopeia A Supernova remnant

Stardust Summary

- Meteorites and cosmic dust contain ~100 ppm of μm-size stardust
- 99% originate from red giant/AGB stars
- 1% originate from novae and supernovae
- Each of the nucleosynthesis processes are recorded among these stardust grains

Stardust Frontier: Silicates

- Silicates are abundant but only recently found
  - Huge background of Solar System silicates
- Commonly observed throughout the Galaxy by astronomers
- Silicates are sensitive recorders of their history
  - Radiation, thermal processing, aqueous alteration
Silicate Stardust Evolution

- **Silicate mineralogy from 10 µm feature**
  - **Evolved stars**: 10 – 20 % crystalline silicates
  - **Diffuse ISM**: ~ 1 % crystalline silicates
  - **Young stars**: mix of crystalline/amorphous & Comets & IDPs
  - **Meteorites**: crystalline silicates dominate

- **Proportion of crystalline silicates**
  - a) 0 %
  - b) 0.2 %
  - c) 0.5 %
  - d) 1 %

Crystalline silicates are rendered amorphous or destroyed on ~ 10 Ma timescale. Re-formed near young stars.

Found! Silicate Stardust in an Interplanetary Dust Particle

Silicate stardust grains are small (<0.5 µm) and hidden within an overwhelming background of solar system silicates

Messenger et al. (2003) Science 300, 105
Presolar Silicate in Acfer 094

Nguyen & Zinner, Science, 2004
Identifying Interstellar Dust in IDPs

Thin section of IDP studied by TEM with typical anhydrous mineralogy

<table>
<thead>
<tr>
<th>Presence</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEMS</td>
<td>FeS</td>
</tr>
<tr>
<td>Enstatite</td>
<td>Ca,Al-rich glass</td>
</tr>
<tr>
<td>Forsterite</td>
<td>Thermally altered silicates</td>
</tr>
</tbody>
</table>

Presolar grain abundances:

- 4 of >100 GEMS
- 2 of >40 forsterite grains
- 0 of >40 enstatite grains
- 0 of 5 anorthite grains
Presolar Silicate Mineralogy

- >150 silicate stardust grains
- 8 amorphous silicates
- 2 Olivine grains

**amorphous:crystalline silicate abundances**

- Interstellar dust: 100:1
- in meteorites, IDPs: 4:1

**Most amorphous interstellar dust is missing**

- Amorphous grains more easily destroyed?
- Annealed into crystalline silicates?
- Not isotopically distinct?

Messenger et al. (2003) Science 300, 105
Stardust Abundances

New ability to probe smaller grains (200 nm)
O-rich stardust grains now known to ‘outweigh’ carbonaceous phases

Zinner (2003) GCA 67, 5083
Nittler (2003) EPSL 209, 259
Messenger et al. (2003) Science 300, 105
Stardust Frontiers

- Ancient materials preserved in meteorites are direct samples of evolved stars and supernovae
- >10 to 100 stars seeded our own solar system
- New samples of cometary material now being searched for stardust
- Have comets better preserved the Solar System starting materials?

First look at the Stardust samples