Opportunities with stardust and Stardust

Andrew M. Davis
Stardust: The mission
stardust: the real thing
Lewis et al. (1987)  
Bernatowicz et al. (1987)  
Amari et al. (1990)
Mainstream SiC
SiC X-grains
SiC Y-grains
SiC Z-grains
SiC AB-grains
SiC C-grains
SiC Nova grains
Si$_3$N$_4$ grains
Graphite grains
Terrestrial

Sun
Earth's atmosphere

Mainstream 93%
A 2.8%
C <<1%
Y 1.5%
Z 1.4%
X 1.2%
Nova <<1%

Davis (2011, PNAS 108, 19142)
Graphite grains

Si (‰)

SiC Nova grains

Si₃N₄ grains

Davis (2011, PNAS 108, 19142)
How do we find presolar grains?

Chemistry (burning down the haystack…)

In situ

Presolar silicate in IDP (Messenger et al. 2003)

Amari, Lewis and Anders
Stardust “telescopes”

Secondary Ion Mass Spectrometry (SIMS)
- Major/minor element isotope ratios (>100nm)

Washington Univ. NanoSIMS

Electron Microscopy
- Morphology/mineralogy/microstructure (>1nm)

Transmission Electron Microscope

Resonance Ionization Mass Spectrometry (RIMS)
- Trace-element isotopes (>1µm)

Argonne “CHARISMA”
Types, abundances, sizes and sources of stardust.

<table>
<thead>
<tr>
<th>Mineral Type</th>
<th>Abund (ppm)</th>
<th>Size (µm)</th>
<th>Stellar source</th>
<th>Relative contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>1400</td>
<td>0.002</td>
<td>SNII; solar system?</td>
<td></td>
</tr>
<tr>
<td>SiC</td>
<td>30</td>
<td>0.3–50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mainstream</td>
<td></td>
<td></td>
<td>AGB (1.5–3 M$_\odot$)</td>
<td>90%</td>
</tr>
<tr>
<td>X</td>
<td></td>
<td></td>
<td>SNII</td>
<td>1.5%</td>
</tr>
<tr>
<td>Y</td>
<td></td>
<td></td>
<td>~1/2 solar metallicity AGB</td>
<td>few%</td>
</tr>
<tr>
<td>Z</td>
<td></td>
<td></td>
<td>~1/4 solar metallicity AGB</td>
<td>few%</td>
</tr>
<tr>
<td>AB</td>
<td></td>
<td></td>
<td>J-stars; born-again AGB</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td>SNII</td>
<td>0.1%</td>
</tr>
<tr>
<td>Nova</td>
<td></td>
<td></td>
<td>Novae</td>
<td>0.1%</td>
</tr>
<tr>
<td>Graphite</td>
<td>10</td>
<td>1–20</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SNII</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AGB (1.5–3M$_\odot$)</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>J-stars; born-again AGB</td>
<td>&lt;10%</td>
</tr>
<tr>
<td>Si$_3$N$_4$</td>
<td>0.002</td>
<td>≤1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SNII</td>
<td>100%</td>
</tr>
<tr>
<td>Oxides</td>
<td>50</td>
<td>0.1–2</td>
<td></td>
<td></td>
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<tr>
<td>Silicates</td>
<td>200</td>
<td>≤1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>AGB (1–2.2 M$_\odot$)</td>
<td>70%</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>AGB (&lt;1.8 M$_\odot$; CBP)</td>
<td>15%</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>AGB (low mass &amp; metallicity); SNII</td>
<td>5%</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>SNII</td>
<td>10%</td>
</tr>
<tr>
<td>N</td>
<td></td>
<td></td>
<td>Novae</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>
$\delta^{94} \text{Mo (‰)}$

$\delta^{97} \text{Mo (‰)}$

$\delta^{98} \text{Mo (‰)}$

$\delta^{100} \text{Mo (‰)}$

$\delta^{96} \text{Zr (‰)}$

$\delta^{95} \text{Mo (‰)}$

$\delta^{94} \text{Mo (‰)}$

$\delta^{97} \text{Mo (‰)}$

$\delta^{98} \text{Mo (‰)}$

$\delta^{100} \text{Mo (‰)}$

$\delta^{96} \text{Zr (‰)}$

[Fe/H] = 0
solar metallicity

2 $M_{\odot}$

old data
new data

D12
D6
D3
D2
D1.5
ST
U1.3
U2

Barzyk et al., 2007
This study

Gallino (pers. comm.)

2 M☉, 1 Z☉

FRUITY (Cristallo et al., 2011)

2 M☉, 1 Z☉
Ti isotopes in refractory inclusions and bulk meteorites

Why are $^{46}$Ti and $^{50}$Ti anomalies correlated? This is hard to achieve by single nucleosynthetic source.
High points of stardust work in the last ten years

• Tens of thousands of grains now analyzed by SIMS
• Measurement of isotopic compositions of many elements (Li, C, N, O, Mg, Ca, Ti, Fe, Ni, Sr, Zr, Mo, Ru, Ba, Nd, Sm, W) in many different kinds of grains
• Discovery of presolar silicates
• Evidence for *in situ* decay of $^{44}$Ti (60 y) and $^{49}$V (330 d) in SN SiC grains
• Two kinds of carbon (diamond and glassy carbon) in presolar “diamond”
• $^{54}$Cr-rich chromian spinel is the carrier of $^{54}$Cr anomalies in carbonaceous chondrite meteorites
High points of stardust work in the last ten years

- Sr, Zr, Mo, Ru, Ba isotopic compositions of single presolar grains have confirmed the general picture of how the s-process elements are produced deep in AGB stars, mixed into the outer parts of those stars and ejected into the interstellar medium (e.g., Lugaro et al., 2003, ApJ 503, 486)

- In situ decay of $^{99}$Tc in mainstream (AGB) SiC grains (Savina et al., Science 303, 649)

- The n-burst isotopic pattern seen in Mo (and Zr, Ru and Ba) shows that X-grains come from Type II supernovae (core collapse of massive stars)
Technical goals for CHILI

- Most of the periodic table with %\text{oo} precision
- 50 % useful yield (CHARISMA: 2 %, SARISA: 25 %)
- 5–10 nm resolution
- Better reliability

- New detector technology
- Improved ion optics (higher extraction voltage)
- FIB ion gun
- Improved hard- and software
UV ps laser pulse = start signal

Time-of-flight Ion detection = stop signal

Field-evaporated ion

Position-sensitive imaging detector

~10^6 x magnification

Sample on sharpened tip apex (r < 50 nm)

Cooled tip (<120 K)

DC voltage (0 to >10 kV)

Local electrode

High E field 10-40 V nm\(^{-1}\) at tip apex:

⇒ controlled field evaporation.

⇒ breaking of surface-atom bonds and ionization.
UV ps laser pulse = start signal

Time-of-flight Ion detection = stop signal

Field-evaporated ion Sample on sharpened apex (r < 50 nm)

Cooled (<120 K)

DC voltage (0 to >10 kV)

Position-sensitive imaging detector ~10^6 x magnification

High E field 10^-40 V nm^-1 at apex:
⇒ controlled field evaporation,
⇒ breaking of surface-atom bonds and ionization.

Methods:
LEAP® Atom-Probe Tomography of Nanodiamonds

Local Electrode Microtip Specimen

Ion Flight Paths

Microtip Specimen

Voltage Pulse HV Contact

OR Laser Pulse

Atomic & Position Sensitive Imaging Detector

Straight Flight Path ‘DT-200’ Shown
Diamond

- Most abundant presolar grain type in meteorites and IDPs, but are they presolar?
  - Some are, based on Xe HL and $r$-process tellurium
  - Carbon isotopic composition is normal
  - $\delta^{15}N = -343 \, \text{‰}$, like the Sun!
  - Two kinds of carbon, diamond (ND) and glassy carbon (GC)

• What fraction of the diamonds are presolar?
  – avg. diameter ~3 nm; ~2000 C atoms per grain
    => single grain C isotope analyses needed
• Atom probe is on the verge of measuring the distribution of $^{12}\text{C}/^{13}\text{C}$ ratios of individual meteoritic nanodiamonds
What’s next?

• How old are presolar grains?
  – *U-Th-Pb dating of single grains* (hard, but maybe possible with improved instrument)

• Disentangling of nucleosynthesis and chemistry as a means of enriching refractory elements
  – *Concentrations and isotopic compositions of the same element in the same grain*

• More detailed tests of nucleosynthesis models
  – *Isotopic compositions of many elements in the same grain; measure new elements*

• Testing models for origin of rare kinds of grains
  – *Isotopic compositions of heavy elements in A, B, X, Y, Z SiC grains, graphite grains, corundum grains*
What’s next?

• Distribution of isotopic compositions within presolar grains
  – *did trace elements enter grains by condensation or implantation?*
  – *Are the isotopic compositions of subgrains in graphite all the same?*

• Measurement at low concentrations
  – *Do low-concentration grains have the same isotopic pattern as high-concentration grains?*
  – *New elements*

• Analysis of contemporary interstellar dust
  – *We now have 3 candidate grains from Stardust mission: are they circumstellar or processed in the ISM?*

• Measurement of C isotopes in single diamond grains
  – *Are all diamonds from supernovae? Are they all presolar?*
Needs of the presolar grains community

• Nuclear reaction rates
  – Neutron-producing rates $^{13}\text{C}(\alpha,n)^{16}\text{O};$ $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$
  – Neutron capture cross sections of key branching isotopes, e.g. $^{85}\text{Kr},$ $^{95}\text{Zr}$

• Stellar models
  – Predictions of isotopic and chemical composition of stellar condensates

• Progress in improving understanding of stellar nucleosynthesis will come from continued close collaboration of stellar modelers and grain analysts
Take-home message

A lot of new data on presolar grains will come in the next ten years, particularly on heavy elements and on elements that are affected by GCE, providing stringent tests of stellar nucleosynthesis models and motivating improved measurements of nuclear reaction rates.