Hands-on Astrophysics

Analysis of Presolar Stardust Grains to Decipher Stellar Nucleosynthesis

Reto Trappitsch



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Illuminated Dust Around Supergiant Star V838 Monocerotis (Credit: NASA, AURA/STScI)

Formation of the elements

Elements that formed during Big Bang nucleosynthesis





Formation of the elements

The rest of the elements - what's left to explain



	140.12 534.4 1.12 58	140.91 527.0 1.13 59	144.24 533.1 1.14 60	(145) 61	150.36 544.5 1.17 62	151.96 63	157.25 593.4 1.20 64	158.93 65 565.8	162.50 573.0 1.22 66	164.93 581.0 1.23 67	167.25 589.3 1.24 68	168.93 596.7 1.25 69	173.05 70	174.97 71 523.5 1.27 71
*	Cerium	Praseodymium	Nd Neodynium	Promethium	Samarium Samarium	Eu Europium	Gadolinium	Tb Terbium	Dysprosium	Ho	Erbium	Tm ³	Ytterbium	Lutetium
	232.04 587.0 1.30 90	231.04 91	238.03 597.6 1.38 92	(237) 93	(244) 94	(243) 578.0 1.30 95	(247) 581.0 1.30 96	(247) 97	(251) 98	(252) 99	(257) 627.0 1.30 100	(258) 635.0 1.30 101	(259) 642.0 1.30 102	(262) 103 470.0
*	Thorium	Protactinium	Uranium	Neptonium	Plutonium	Americium [Rn] 5/7 781	Curium [8n] 51' 60' 76'	Berkelium (Rn) Sf 76'	Californium	Es Einsteinium	Fm Fermium (Re) Sf ¹¹ 7v ¹	Mendelevium	Nobelium (Re) SP4 76 ³	Lawrencium [8n] Sf ¹⁴ 7n ¹ 7p ¹

Stellar nucleosynthesis – the three main processes (Burbidge et al., 1957)



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Solar System formation from average material in Milky Way

- Formation of the first Solar System solids: 4.567 Ga ago
- Composition of the solar nebula defined by galactic chemical evolution (GCE)
- GCE of Milky Way prior to Solar System formation: $\sim 9\,{\rm Ga}$

Understanding the origin of the Solar System requires knowledge on how the formation took place and where its material originated



The witnesses of the early Solar System

Meteorites

- Unaltered, primitive meteorites
- Analyze solar nebula composition
- Short-lived radionuclides to inform early Solar System timing

Presolar grains

- Incorporated into meteorite parent bodies
- Bona fide stardust
- Recorded the composition of their parent star



Presolar SiC grain from Murchison CM2 chondrite



Stardust grains

Presolar grains: stellar remnants



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Presolar stardust and their parent stars

- δ -units: Deviation from solar (%)
- Presolar grains identified by their extreme isotopic composition
- SiC grains: best studied samples
- Classified by analyzing their Si, C, and N isotopic composition
- Carry their parent stars isotopic composition
- Hands-on astrophysics samples
 - Galactic chemical evolution
 - Stellar nucleosynthesis
 - Transport processes in the interstellar medium

SiC Mainetream SiC X-grains SiC Y-grains SiC Z-grains 200 SiC A-grains SiC C-grains SiC Nova grains Si_N₄ grains Graphite grains Silicate grains δ²⁹Si (‰) -200 2.000 -600 1.000 -900 -600 -400 -200 n -800 200 --1 000 0 1.000 2.000 3.000 δ³⁰Si (‰) 830 Si (%)

Davis (2011)

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Presolar stardust and their parent stars

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Classification: Analyzing the grain's C, Si isotopic compositions

- Analyze the isotopic composition of Si, C, (N) in SiC grains
- NanoSIMS: Nanoscale Secondary Ion Mass Spectrometer
- Secondary ions analyzed
 → prone to isobaric interferences
- Ideal instrument to measure major isotopic composition



Trace element isotopic analyses

- Resonance Ionization Mass Spectrometry (RIMS)
- Most sensitive technique available for atom-limited samples
- $\bullet~$ Up to $\sim 40\%$ useful yield
- Only two instruments worldwide that analyze presolar grains
 - LION at Lawrence Livermore National Laboratory
 - CHILI at the University of Chicago



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Н	A RIMS Periodic Table											He					
Li	Ве	e accessible by RIMS							в	С	Ν	0	F	Ne			
Na	Mg		published RIMS isotopic measurements						AI	Si	Ρ	S	CI	Ar			
κ	Са	Sc	Ti	۷	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Мо	Тс	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Те	_	Xe
Cs	Ва	*	Hf	Та	W	Re	Os	Ir	Pt	Au	Hg	F	Pb	Bi	Po	At	Rn
Fr	Ra	**															
		*	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Но	Er	Tm	Yb	Lu
		**	Ac	Th	Pa	u	Np	Pu	Am	Cm	Bk	Cf	Fs	Em	Md	No	Lr

Savina and Trappitsch (2019)





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Simultaneous analysis of Fe and Ni by RIMS



Simultaneous analysis of Fe and Ni by RIMS









Pleiades (NASA/ESA/AURA/Caltech)

Hydrostatic equilibrium - Gravity vs. nuclear burning



Stellar lifetimes – the James Dean syndrome

• Mass luminosity relationship

 $L \propto M^{3.5}$

- Stellar lifetimes τ depends on fuel availability
 - $egin{array}{ccc} au & \propto & M \ au & \propto & L^{-1} \end{array}$
- Sun can burn \sim 10% of its H • $\tau \approx$ 10 Gyr
 - $au = 10~{
 m Gyr} \left(rac{M}{M_{\odot}}
 ight)^{-2.5}$



Life and death of a low-mass star (0.4 $M_\odot \lesssim M \lesssim$ 4 M_\odot)

- Solar core now: $T_9 \approx 15$, $ho \approx 150\,{
 m g\,cm^{-3}}$
- H runs out: core contracts, H-shell burning
- Envelope becomes convective
- Meanwhile, the core keeps contracting until degenerate
- He is added and temperature rises
- He ignites He-flash: a thermonuclear runaway (for M ≤ 2 M_☉)
 → Energy goes into lifting degeneracy
- Quiet He burning to CO core
- CO core w/ He, H burning shells
- H burning adds He until ignition



Asymptotic giant branch (AGB) stars

- Star expands rapidly, and cools
- Cycles between H and He burning \rightarrow Thermally pulsing AGB star
- AGB stars are copious dust producers
- Slow neutron capture (*s*-) process forms elements along the valley of stability
- Two important neutron sources:
 - ¹³C(α, n)¹⁶O
 - ²²Ne(α , n)²⁵Mg



Two neutron sources are at work



13 C(lpha, n) 16 O

• Main s-process neutron source

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- $Max < 10^7 \, n \, {\rm cm}^{-3}$
- 1000s of years

$^{22}\mathsf{Ne}(lpha, \mathit{n})^{25}\mathsf{Mg}$

- Bottom of He intershell
- Max $5 \times 10^9 \, n \, \mathrm{cm}^{-3}$
- A few years

A more detailed look into the ¹³C pocket



What to look in stardust grains



Who wins: Neutron capture or β^- -decay

• Branching ratio f_n

$$f_n = \frac{\lambda_n}{\lambda_n + \lambda_\beta}$$

- Neutron capture rate
 - $\lambda_n = N_n v_T \langle \sigma \rangle$
- β^- -decay rate

$$\lambda_{\beta} = \frac{\ln(2)}{T_{1/2}}$$



Stephan et al. (2019)

- δ-units: deviation of isotope ratio from solar system average value (usually in ‰)
- SiC grains can only condense in carbon-rich areas, with C>O
- Heavier-mass stars get hotter \rightarrow Activate ²²Ne neutron source more \rightarrow Activate ⁹⁶Zr production more
- Additional complication: Nuclear physics input uncertainties, e.g., $^{95}{\rm Zr}({\rm n},~\gamma)$ cross section
- Comparison of isotope with stardust measurements allows determination of parent stars



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Multi-element measurements to constrain the ¹³C-pocket

- Formation, size, mass of ¹³C-pocket remain poorly understood
- Multi-element isotopic measurements in individual grains can help to decipher the physics
- Study by Liu et al. (2015) for Sr, Ba ightarrow
- Many possible ¹³C-pocket configurations can explain the measurements
- One set of model must fulfill all measurements constraints simultaneously



Liu et al. (2015)

Stardust analyses from AGB stars enable tight constraints on *s*-process

- Existing multi-element measurements constrain the *s*-process
- Large uncertainties of existing measurements
- New RIMS techniques allow simultaneous, precision measurements of Zr, Ba, and W
- ¹³⁸Ba: Neutron magic
 - \rightarrow Bottle neck for neutron flux
- Zr and W isotopes
 - On either side of Ba
 - Branch points to constrain activation of ²²Ne neutron source



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▲ ₽ 76	Os 181 105 m	Os 182 21.84 h	Os 183 13.0 h	Os 184 0.02 584±49mb	Os 185 92.95 d	Os 186 1.59 414±17mb	Os 187 1.96 969±32mb	Os 188 13.24 294±14mb	Os 189 16.15 1083±30mb
	Re 180 2.46 m	Re 181 19.9 h	Re 182 64.2 h	Re 183 70.0 d	Re 184 35.4 d	Re 185 37.40 1439±58mb	Re 186 3.7183 d 747±363mb	Re 187 62.60 7.8 ky 1184±60	Re 188 17.0040 h
74	W 179 37.05 m	W 180 0.12 656±64mb	W 181 121.2 d	W 182 26.50 285±11mb	W 183 14.31 574±25mb	W 184 30.64 225±27mb	W 185 75.1 d 66.9 d 633±142mb	W 186 28.43 226±12mb	W 187 24.000 h
	Ta 178 2.36 h	Ta 179 1.82 y 1334±422mb	Ta 180 0.012101 ^{1827±114mb}	Ta 181 99.98799 814±11mb	Ta 182 114.74 d 51.8 d 1120±180ml	Ta 183 5.1 d	Ta 184 8.7 h	Ta 185 49.4 m	Ta 186 10.5 m
72	Hf 177 18.60 1653±21mb	Hf 178 27.28 338±4mb	Hf 179 13.62 992±8mb	Hf 180 35.08 165±2mb	Hf 181 42.39 d 32.6 d 194±31mb	Hf 182 8.90 My-3 39.8 ky 141±8mb	Hf 183 1.018 h	Hf 184 4.12 h	Hf 185 3.5 m
	Lu 176 2.599 - 5.3 ky 1639±14	Lu 177 6.6457 d ⁻³ 5.9 d	Lu 178 28.4 m	Lu 179 4.59 h	Lu 180 5.7 m	Lu 181 3.5 m	Lu 182 2.0 m	Lu 183 58 s	Lu 184 20 s
		106		108		110		112	2

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