# Zirconium Isotope Abundances in Single Mainstream SiC Grains and the $^{13}$C Pocket Structure in AGB Models

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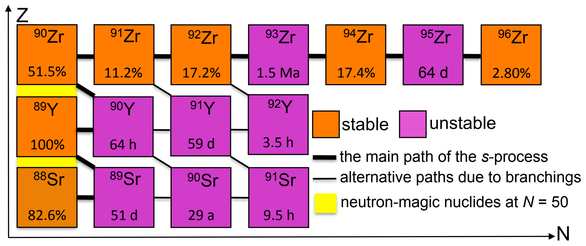
## Introduction



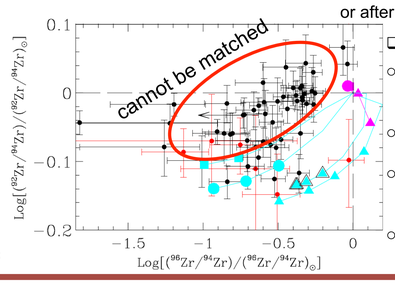

### ◆ AGB Model Uncertainties

- ❑ Nuclear inputs
  - ○ neutron capture cross sections
    Maxwellian Averaged Cross Sections (MACSs)
  - ○ $^{22}$Ne($\alpha$,n)$^{25}$Mg reaction rate
    ~a factor of 4 uncertainty at relevant AGB stellar T (Jaeger *et al.* 2001, Longland *et al.* 2012)
- ❑ Stellar model
  - ○ $^{13}$C pocket formation
    uncertain mixing process(es) occurred during and/or after its formation.

### ◆ AGB Model Predictions for Zr Isotopes

(Lugaro *et al.* 2014)

- ❑ New n-TOF cross sections
- ❑ Stellar model (Karakas 2010)
- ❑ Failed to explain mainstream grains with $\delta(^{92}Zr/^{94}Zr) > -50$‰




- ❑ Fig.3 of Lugaro *et al.* (2014)
  - ○ **black dots**: presolar SiC, Nicolussi *et al.* (1997) & mainstream SiC, Barzyk *et al.* (2007);
  - ○ **red dots**: presolar graphite, Nicolussi *et al.* (1998);
  - ○ **colored lines with symbols**: their AGB model predictions for carbon-rich phase;
  - ○ **colored lines without symbols**: predictions for oxygen-rich phase.

## Grain Data & Torino AGB Model

### ◆ Previous RIMS Data

- ❑ Nicolussi *et al.* (1997) & Barzyk *et al.* (2007), delta-notation with 2σ errors

### ◆ A Parameterized $^{13}$C Pocket

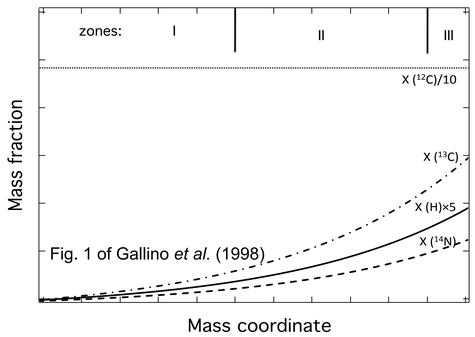



Fig. 1 of Gallino *et al.* (1998)

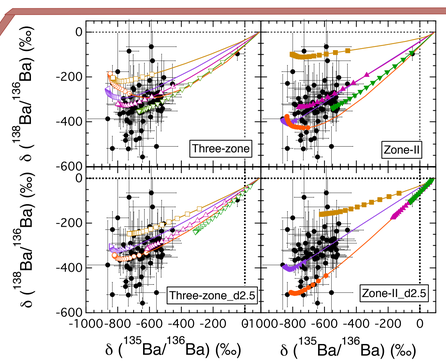
| ST $^{13}$C pocket | Zone-I (Innermost) | Zone-II (Middle) | Zone-III (Outermost) |
|---|---|---|---|
| Total M ($M_\odot$) | $4.00\times10^{-4}$ | $5.30\times10^{-4}$ | $7.50\times10^{-6}$ |
| $X(^{13}C)$ | $3.20\times10^{-3}$ | $6.80\times10^{-3}$ | $1.60\times10^{-2}$ |
| $X(^{14}N)$ | $1.07\times10^{-4}$ | $2.08\times10^{-4}$ | $2.08\times10^{-3}$ |

- ❑ Three parameters to define a $^{13}$C pocket
  - ○ **$^{13}$C distribution**: Three-zone (decreasing) *vs.* Zone-II (flat)
  - ○ **$^{13}$C pocket mass:** a factor of eight variation
  - ○ **$^{13}$C efficiency**: $X(^{13}C)$ (D3 to U2 cases in the literature)

### ◆ Previous Constraints (Liu *et al.* 2014a)

- ❑ Constraints on the $^{13}$C pocket

| $\delta^{138}$Ba | > −400‰ | < −400‰ |
|---|---|---|
| $^{13}$C profile | Three-zone Zone-II | Zone-II |
| $^{13}$C mass fraction | D3−U1.3 | around ST |
| $^{13}$C pocket mass upper-limit | $18.6\times10^{-4}$ $M_\odot$ | $5.3\times10^{-4}$ $M_\odot$ |
| $^{13}$C pocket mass lower-limit | $7.4\times10^{-4}$ $M_\odot$ | $2.1\times10^{-4}$ $M_\odot$ |




- ○ **black dots**: acid-cleaned mainstream SiC Liu *et al.* (2014a,b);
- ○ **colored lines with symbols**: Torino AGB model predictions for carbon-rich phase;
- ○ **colored lines without symbols**: predictions for oxygen-rich phase.

- ❑ Constraints on $^{22}$Ne($\alpha$,n)$^{25}$Mg reaction rate
  **¼×K94−K94** (K94:lower-limit by Käppeler *et al.* 1994)

### ◆ New n-TOF Zr neutron capture cross-section ($\sigma^i_{code}$)

| Isotope | LDG03[a] 8 keV | 23 keV | 30 keV | 1σ err (30 keV) | This work[b] 8 keV | 23 keV | 30 keV | 1σ err (30 keV) |
|---|---|---|---|---|---|---|---|---|
| $^{90}$Zr | 18.9 | 20.8 | 21.0 | 9.5% | 18.1 | 18.8 | 19.3 | 4.7% |
| $^{91}$Zr | 90.5 | 64.7 | 60.0 | 13.3% | 87.3 | 67.4 | 63.0 | 6.3% |
| $^{92}$Zr | 47.2 | 34.6 | 33.0 | 12.1% | 50.1 | 38.5 | 38.0 | 8.0% |
| $^{93}$Zr | 128.0 | 103.0 | 95.0 | 10.5% | 127.9 | 102.8 | 95.0 | 9.4% |
| $^{94}$Zr | 30.1 | 26.6 | 26.0 | 3.8% | 30.2 | 29.8 | 30.5 | 6.5% |
| $^{95}$Zr* | 111.1 | 85.2 | 79.0 | 15.0% | 55.5 | 42.6 | 39.5 | 15.0% |
| $^{96}$Zr | 18.1 | 11.1 | 10.7 | 4.7% | 17.2 | 10.9 | 10.3 | 6.0% |

**References**: Tagliente *et al.* 2008a,b, 2010, 2011a,b, 2013

$$\sigma^i_{code} = \frac{<\sigma^i v>}{v_T(30keV)} = \frac{\sigma^i_{MACS} v_T}{v_T(30keV)} \quad (\sigma^i_{MACS} = \frac{<\sigma^i v>}{v_T})$$

- ○ For most of the nuclides along the *s*-process path, their $\sigma^i_{MACS}$ values follow the $1/v_T$ rule (Clayton D. D. 1968);
- ○ If so, their $\sigma^i_{code}$ values stay constant at different stellar T;
- ○ The $\sigma^i_{code}$ values of $^{91,92}$Zr deviate from the $1/v_T$ rule by 30 % from 8 keV to 23 keV.

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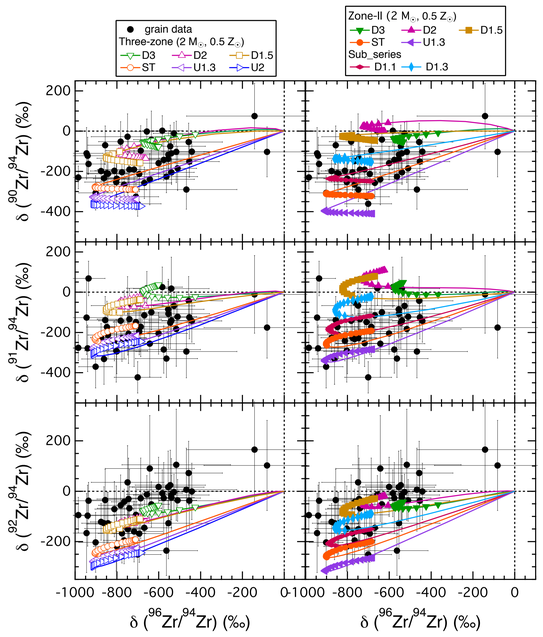
## Result & Discussion

### ◆ Effect of the $^{13}$C Pocket Structure




- ○ **black dots**: presolar SiC from Nicolussi *et al.* (1997) & mainstream SiC from Barzyk *et al.* (2007);
- ○ **colored lines with symbols**: Torino AGB model predictions for carbon-rich phase;
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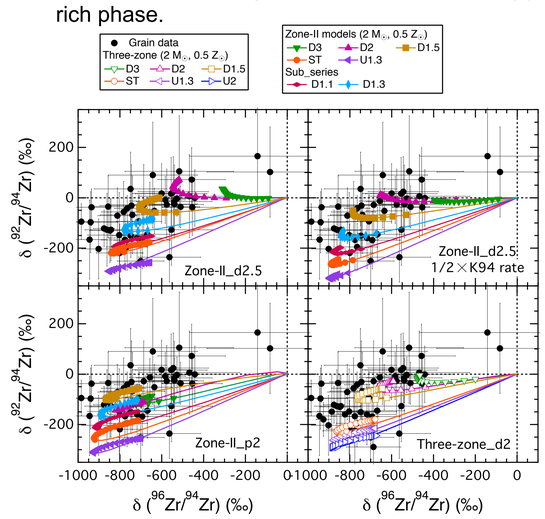
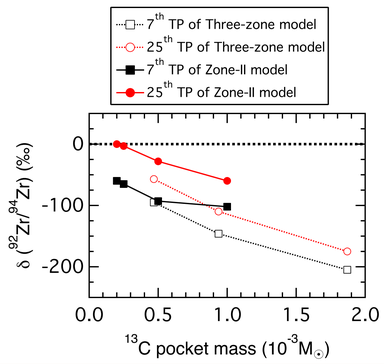



### ◆ Effect of the $^{13}$C Pocket Mass




- ❑ Why are $\delta^{90,91,92}$Zr predictions affected by the $^{13}$C pocket?
  - ○ $\delta^{90}$Zr: $^{90}$Zr is neutron magic, the bottleneck of the *s*-process path;
  - ○ $\delta^{91,92}$Zr: $^{91,92}$Zr MACS values deviate from the $1/v_T$ rule by 30 % while that of $^{94}$Zr closely follows this rule.
- ❑ What is the effect of the $^{92,94}$Zr MACS uncertainty on $\delta^{92}$Zr predictions ?
  - ○ By adopting both the lower-limit $^{92}$Zr & upper-limit $^{94}$Zr MACSs, $\delta^{92}$Zr predictions are shifted by 100 ‰; better match with the grain data can be achieved;
  - ○ Better determination of $^{92,94}$Zr MACSs is needed to evaluate the necessity of Zone-II models.

## Conclusion

- ❑ In order to explain $\delta^{92}$Zr >−50 ‰, **a physically smaller $^{13}$C pocket with either Three-zone (conventional) or Zone-II (flat)** $^{13}$C pocket needs to be adopted in Torino AGB model calculations;
- ❑ Our correlated Sr and Ba isotopic composition (Liu *et al.* 2014b) of presolar SiC grains suggest that **most of the grains** came from AGB stars with **a smaller $^{13}$C pocket with a Three-zone** pocket structure;
- ❑ For **a few grains** with $\delta^{138}$Ba<−400 ‰, they can only be explained by model calculations with **a smaller Zone-II** $^{13}$C pocket;
- ❑ To summarize, Sr, Zr and Ba isotopes in mainstream grains all consistently point toward **a smaller $^{13}$C pocket**;
- ❑ Different $^{13}$C pocket structures should be **a result of different degrees of mixing** during or after the formation of the $^{13}$C pocket;
- ❑ For the first time, we discovered **the smoking guns of the $^{13}$C pocket (Sr, Zr and Ba);** the derived constraints will guide future simulations of $^{13}$C pocket formation;
- ❑ **Correlated Sr, Zr and Ba isotope measurements** in acid-cleaned presolar SiC grains will be done soon with CHILI.

**References** [1]Jaeger et al. (2001) PRL, 87, 20; [2] Longland et al. (2012) PRC, 85, 065809; [3] Lugaro M. et al. (2014) *ApJ*, *780*, 95; [4] Karakas A. I. (2010) *MNRAS*, *403*, 1413; [5] Nicolussi G. K. et al. (1997) *Science*, *277*, 1281; [6] Barzyk J. G. et al. (2007) *MAPS*, *42*, 1103; [7] Nicolussi G. K. et al. (1998) *ApJ*, *504*, 492; [8] Gallino R. et al. (1998) *ApJ*, *497*, 388; [9] Liu N. et al. (2014a) *ApJ*, accepted; [10] Liu N. et al. (2014b) *LPS 45*, #2049; [11] Käppeler F. et al. (1994) *ApJ*, 437, 396; [12] Tagliente G. et al. (2008a) *Phys. Rev. C*, *77*, 035802, (2008b) *Phys. Rev. C*, *78*, 045804, (2010) *Phys. Rev. C*, *81*, 055801, (2011a) *Phys. Rev. C*, *84*, 015801, (2011b) *Phys. Rev. C*, *84*, 055802, (2013) *Phys. Rev. C*, *87*, 014622; [13] Clayton, D. D. 1968, Principles of Stellar Evolution and Nucleosynthesis (New York: McGraw-Hill).