Sr, Y and Zr from rotation induced s process in massive stars

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Standard s process in massive stars

S-process production site

- Where?: He-core, C-shell and He-shell burning
- Temperatures: $\gtrsim 2.5 \times 10^8$ K ⇒ activation at end of He-burning (M$\gtrsim$ 13 $M_\odot$)

Neutron economy

- Main neutron source: ^{22}Ne(α,n)^{25}Mg
- Origin of ^{22}Ne: CNO are mainly transformed to ^{14}N. The ^{22}Ne is produced via ^{14}N(α,γ)^{18}F(β^+)^{18}O(α,γ)^{22}Ne
- Other sources (recycling): ^{13}C(α,n)^{16}O, ^{17}O(α,n)^{20}Ne
- Seeds: Iron group nuclei (mainly: ^{56}Fe)
- Poisons - He-burning: ^{22}Ne, ^{25}Mg, ^{16}O, ^{12}C
- Poisons - C-burning: ^{24}Mg, ^{25}Mg, ^{20}Ne, ^{16}O
- Neutron densities: 10^6-10^7 cm^{-3}/10^{10}-10^{11} cm^{-3}

⇒ Source and seeds are secondary, but poisons are primary!

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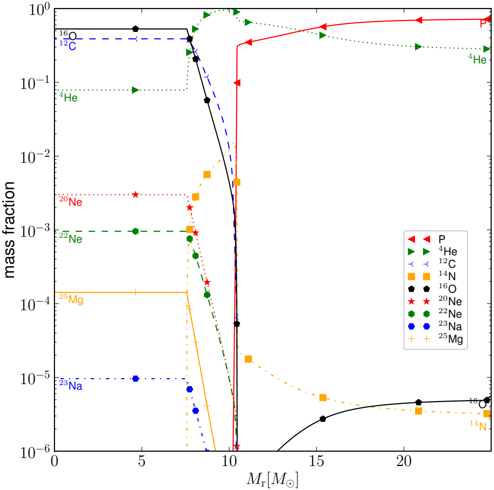
How does the s process in massive stars change, if the source is primary?

Primary ^{22}Ne production due to rotation

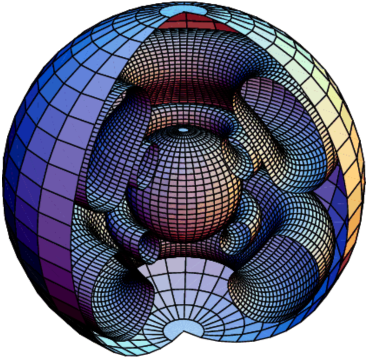
- Primary ^{22}Ne was found in models of massive rotating stars (Meynet et al 2006, Hirschi 2007).
- Possible primary ^{22}Ne production: primary carbon transformed by $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(p,\gamma)^{14}N$ and $^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O(\alpha,\gamma)^{22}Ne$ ⇒ mixing is necessary to produce primary ^{22}Ne.
- Primary ^{12}C is mixed up from He-core transformed to ^{14}N just below the convective H-shell.
- Is ^{14}N mixed back down before the end of He-burning? How much? How is the s process affected?
- The standard s process in massive stars is limited at low Z by available ^{22}Ne, primary production could boost the nucleosynthesis (Pignatari et al 2008).



Geneva stellar Evolution Code - GenEC

1.5D hydrostatic code:

- Rotation: Transport of angular momentum - meridional circulation treated as advection & shear as diffusion (e.g. Meynet & Maeder 1997)
  Transport of chemical elements - also meridional circulation is treated as diffusion (Chaboyer & Zahn 1992)
- Mass loss: takes into account rotation (Maeder & Meynet 2000, Vink et al 2001, de Jager et al 1988)
- Reaction Network: parallelised version of "Basel" network (e.g. Hix and Thielemann 1999)
- Models: from ZAMS to O-burning



Grid of massive star models

- GenEC including BasNet: models until O-burning
- Number of included nuclear species: 613 (He-burning), 737 (from start of C-burning onwards)
- Stellar masses: 15, 20, 25, and 40 $M_\odot$
- Composition: solar - Asplund et al 2005 (isotopic ratios Lodders et al 2003)
  α-enhanced for sub-solar metallicities
  Metallicites: $Z_{\rm ini} = 0.014,\ 10^{-3}$, and 10^{-5} (10^{-7})
  $[{\rm Fe/H}]_{\rm ini} = 0.0,\ -1.8$, and -3.8 (-5.8)
- Rotation rates: $\upsilon_{\rm ini}/\upsilon_{\rm crit} = 0.0$ and 0.4
- Secular shear from Talon & Zahn 1997
- Important reactions:
  ^{22}Ne(α,n)/(α,γ) - Jaeger et al 2001/NACRE
  ^{12}C(α,γ)^{16}O - Kunz et al. 2002
  3α - Fynbo et al 2005
  ^{14}N(p,γ)^{15}O - Imbriani et al 2005

^{22}Ne in rotating massive stars with $\upsilon_{\rm ini}/\upsilon_{\rm crit} = 0.4$

Table: Mass fraction of burned ^{22}Ne in convective He-core

Z \ Mass [$M_\odot$]	15	20	25	40
0.014	7.3e-3	8.5e-3	1.1e-2	1.4e-2
1e-3	1.1e-3	4.1e-3	4.8e-3	3.9e-3
1e-5	5.6e-4	1.8e-3	1.4e-3 (4.5e-3)	3.2e-3
1e-7	-	-	1.2e-4 (5.4e-3)	-

With $\upsilon_{\rm ini}/\upsilon_{\rm crit} = 0.4$ primary ^{22}Ne decreases towards lower Z, but the neutron/seed ratio increses.

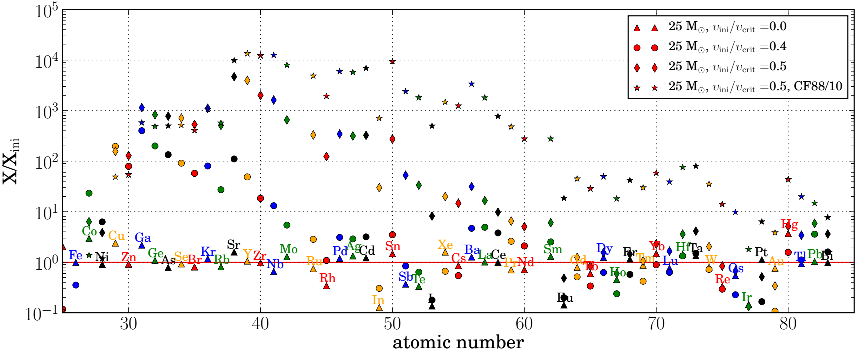
Table: Mass fraction of ^{22}Ne in the He-shell before SN

Z \ Mass [$M_\odot$]	15	20	25	40
0.014	1.4e-2	2.0e-2	1.6e-2	1.2e-2
1e-3	7.6e-3	3.2e-2	2.0e-2	1.7e-2
1e-5	7.6e-3	1.7e-2	1.2e-2 (1.6e-2)	8.6e-3
1e-7	-	-	1.5e-2 (2.0e-2)	-

$\Rightarrow$ 1 to 3% available for explosive nucleosynthesis (? - e.g. Rauscher et al 2002).

Uncertainties of rotation boosted s process

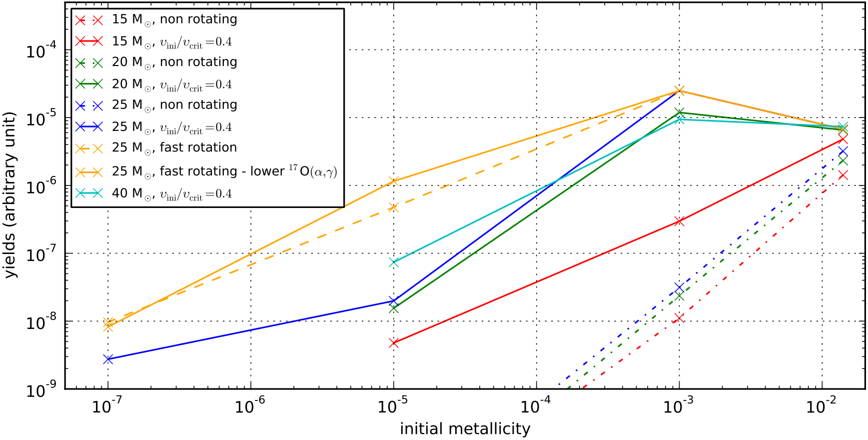
Overproduction factors of 25 $M_\odot$ models with Z= 10^{-5} ([Fe/H] = −3.8)



- The s-process efficiency varies strongly depending on the initial angular momentum/velocity, i.e. on the amount of primary ^{22}Ne.
- Important: Uncertainties in reaction rates (e.g. $^{17}O(\alpha,\gamma)$), defining the strength of neutron poisons, introduce a large uncertainty at low Z.

Yields

IMF weighted ^{88}Sr pre-SN yields

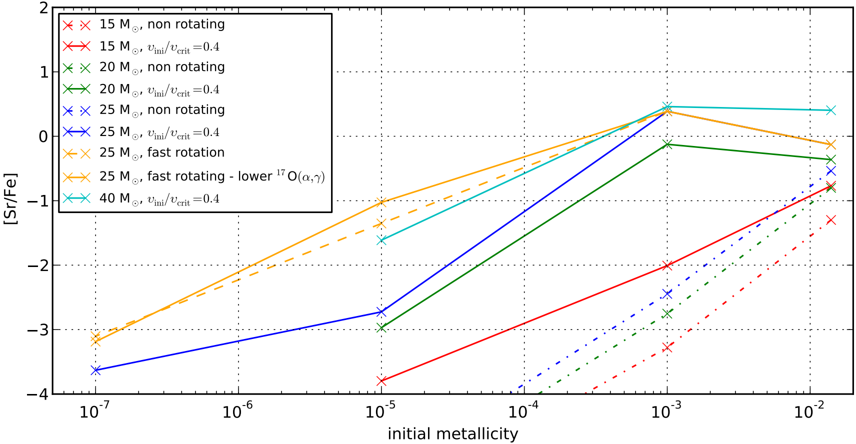


The similar pattern is found for ^{86}Sr, ^{87}Sr, ^{89}Y and ^{90}Zr

Characteristics of boosted s process

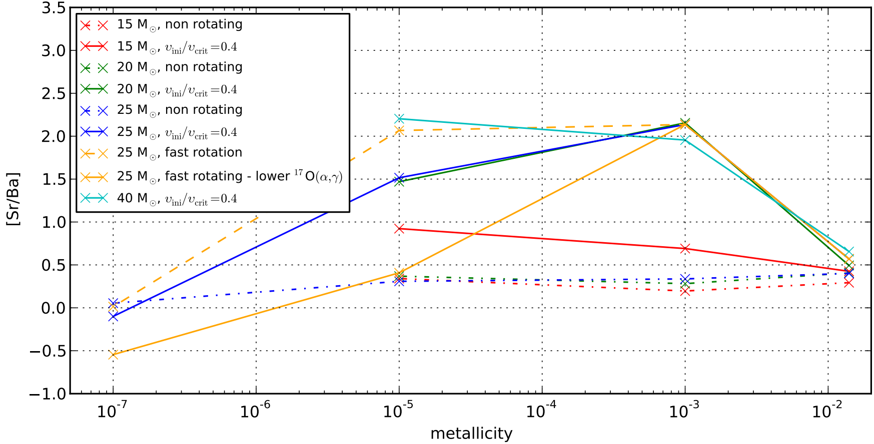
- The production of Sr-peak elements is most efficient for $M = 25\ M_\odot$ $\Rightarrow$ It is essential to know for which stars black hole formation without ejecta.
- Standard s process (without primary ^{22}Ne) occurs only for $[Fe/H] > -2$ (Prantzos et al 1990). Rotational mixing considerably enhances the s-process yields.
- Clearly no primary s-process production, but strong production of Sr-peak elements at $-1 > [Fe/H] > -2$.

S-process signature I



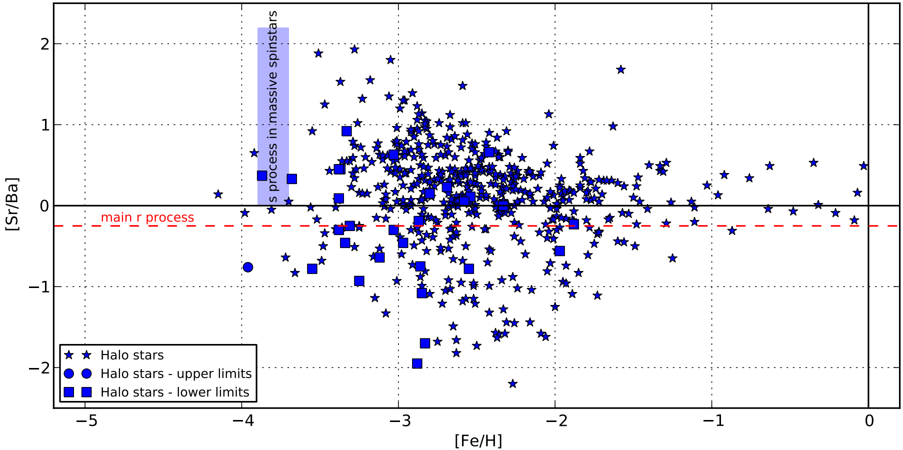
Assumption: 0.1 M$_\odot$ ^{56}Fe is ejected.

S-process signature II



Most efficient models produce [Sr/Ba]=+1 to +2.

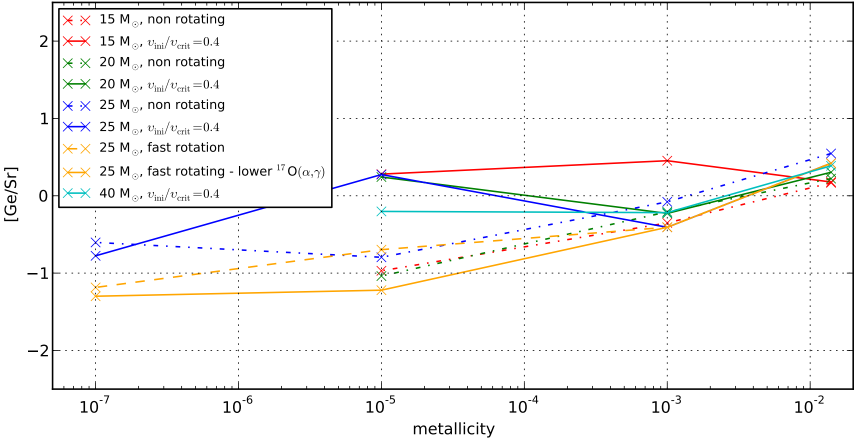
Is this s-process signature observable?



Halo stars: compilation - Frebel 2010

Main r-process: Sneden et al 2008

S-process signature III



Compared to [Sr/Ba], the scatter in [Ge/Sr] is from weaker.

Observational quantities

- Not much Ba is produced $\Rightarrow$ typically $[\mathrm{Sr}/\mathrm{Ba}] = +0.0$ to $+2$ by massive stars with initial $[\mathrm{Fe}/\mathrm{H}] > -4$.
- $[\mathrm{Sr}/\mathrm{Ba}]$ has a strict upper limit of about $+2.3$.
- Scatter $[\mathrm{Sr}/\mathrm{Ba}]$ is intrinsic to s process boosted by rotation.
- $[\mathrm{Ge}/\mathrm{Sr}]$ is increasing from ≈ -1 (at initial $[\mathrm{Fe}/\mathrm{H}] = -5.8$) to $\approx +0.4$ (at initial $[\mathrm{Fe}/\mathrm{H}] = 0$).
- $[\mathrm{Sr}/\mathrm{Zr}] = 0$ to $+1$.
- Models with rotation (e.g. Meynet et al 2006) could also reproduce nitrogen enhancement found in metal-poor halo stars by e.g. Spite et al 2005 (Chiappini et al 2006).

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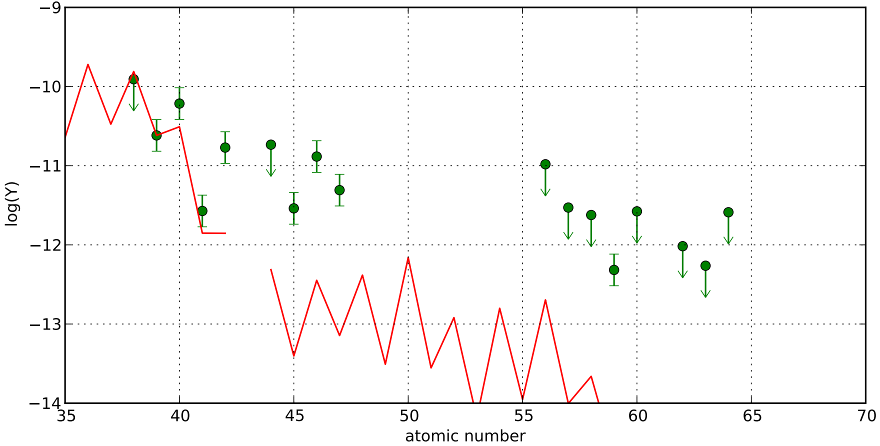

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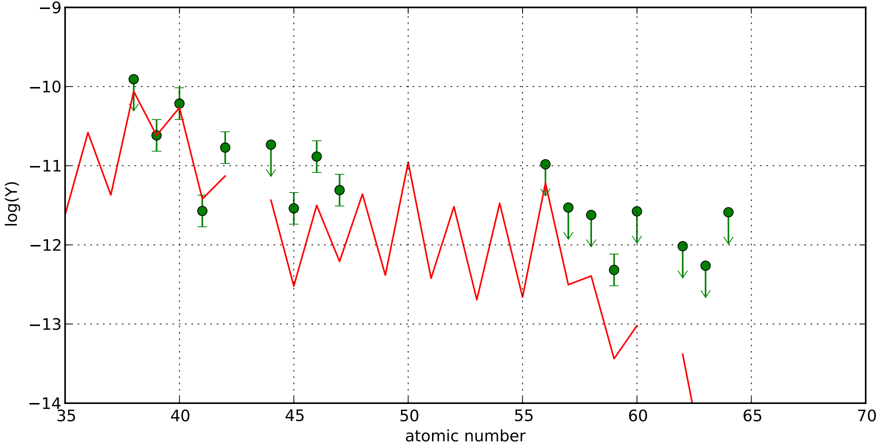

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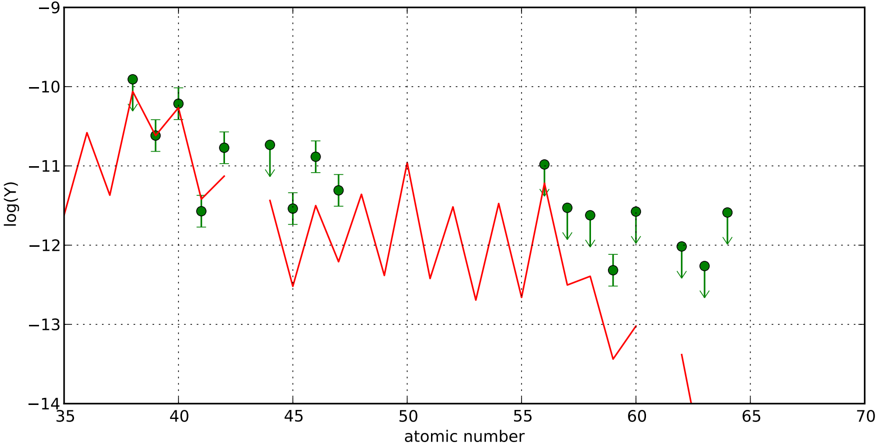

No! ⇒ If a single process is responsible for the LEPP signature, it is probably not the s process in massive stars.

Summary & Conclusion

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- Rotational mixing leads to primary production of ^{22}Ne: 0.1 to 1% in He-core and 1 to 3% in He-shell.
- The efficiency of s process in massive stars (M$\gtrsim$15 M$_\odot$ - ?) is increased by primary ^{22}Ne, at all [Fe/H]$_{\rm ini}$. But there is no "primary" behaviour, because the seeds are secondary and poisons primary.
- Massive stars with rotation show a production peak of Sr, Y and Zr between [Fe/H] ≈ -2 and -1.
- Yields of Sr-peak elements are increased by a factor 2 to 3 at $Z = Z_\odot$.
- A large scatter in s-process abundances is expected from rotating massive stars at sub-solar Z. Typically [Sr/Ba] $\approx +0.0$ and $+2$.
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Outlook

- How does this boosted s process appear in GCE?
- Comparison to low Z r-process poor stars.

Rotation in GENEC

- Transport of angular momentum (Zahn et al. 1992, Meynet and Maeder 1997)

$$\rho \frac{d}{dt}\left(r^2\Omega\right)_{M_r} = \frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \Omega U(r)\right) + \frac{1}{2r^2}\frac{\partial}{\partial r}\left(\rho \nu r^4 \frac{\partial \Omega}{\partial r}\right)$$

- Mixing of chemical species can still be done by diffusion (Chaboyer & Zahn 1992)
- Mixing by meridional circulation (D_h Zahn 1992)

$$D_{\mathrm{mer}} = \frac{|rU(r)|^2}{30 D_{\mathrm{h}}}$$

- shear diffusion coefficient of Talon & Zahn 1997 (Maeder 1997 - similar but without D_{h})

$$D_{\mathrm{shear}} = \frac{(K + D_{\mathrm{h}})}{\left[\frac{\varphi}{\delta}\nabla_\mu(1 + \frac{K}{D_{\mathrm{h}}}) + (\nabla_{\mathrm{ad}} - \nabla_{\mathrm{rad}})\right]} \frac{\alpha H_{\mathrm{p}}}{g\delta}\left(0.8836\Omega \frac{d\ln\Omega}{d\ln r}\right)^2,$$

Reaction rates

- important rates:
  - $^{14}N(p,\gamma)^{15}O$ - Imbriani et al 2005
  - 3α - Fynbo et al 2005
  - $^{12}C(\alpha,\gamma)^{16}O$ - Kunz et al. 2002
  - $^{22}Ne(\alpha,n)^{25}Mg$ - NACRE/Jaeger et al 2001
  - $^{17}O(\alpha,n)/(\alpha,\gamma)$ - NACRE/CF88
- p-, α-captures: NACRE (Angulo et al. 1999)
  - theoretical - Rauscher & Thielemann 2000
- e^{-}-captures: Fuller, Fowler & Newman 1982
- n-captures: experimental - KADoNiS
  - theoretical - Rauscher & Thielemann 2000
- decays: T-dependent - Takahashi & Yokoi 1987
  - NETGEN (Aikawa et al 2005)
  - constant - experimental