STARS, PLANETS AND GALAXIES 2018

Stellar Nucleosynthesis and Yields

George Angelou

Stellar Evolution Group,
Max-Planck-Institut für Astrophysik
Garching, Germany

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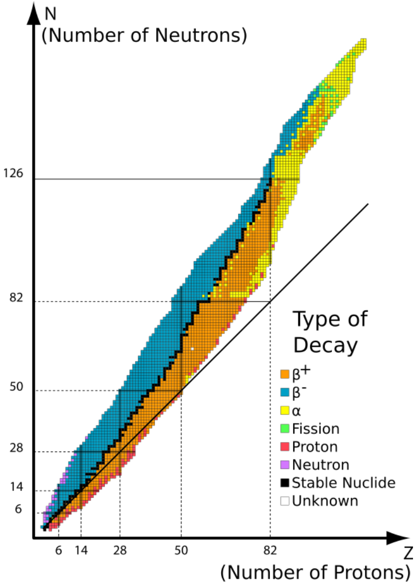
(A 3D printed chart of the nuclides at Monash University)

Multidisciplinary field that ties together many of the talks here!

- Stellar Evolution (all masses)
- Mixing and Stellar Processes
- Spectroscopy
- Nuclear and Quantum Physics (theoretical and experimental)
- Cosmochemistry
- Terrestrial and Meteoritic Chemistry
- Cosmology
- Galactic Chemical Evolution
- Neutrino Astrophysics
- IMF
- ISM
- Hydrodynamics

- By what means and in which quantities are the naturally occurring isotopes produced?
- What are their astrophysical sites?



1957 - B^{2}FH AND CAMERON

REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

*Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California*

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

NUCLEOSYNTHETIC PROCESSES

- Hydrogen burning (pp, CNO, NeNa, MgAl)
- Helium burning (3α)
- Advanced burning (α-captures, C, Ne, O, Si, QSE)

} Hydrostatic burning ($A \leq 60$)

- **NSE (iron peak Sc – Se)**

} Explosive burning ($48 \leq A \leq 84$)

- **s-process**
- i-process
- **r-process**

} Neutron captures ($A > 56$)

- p-process (relatively n-poor stable nuclei)
- rp-process
- irp-process
- αp-process
- γ-process (disintegration of s/r nuclei)

} A ≥ 74 (between ^{74}Se and ^{196}Hg)

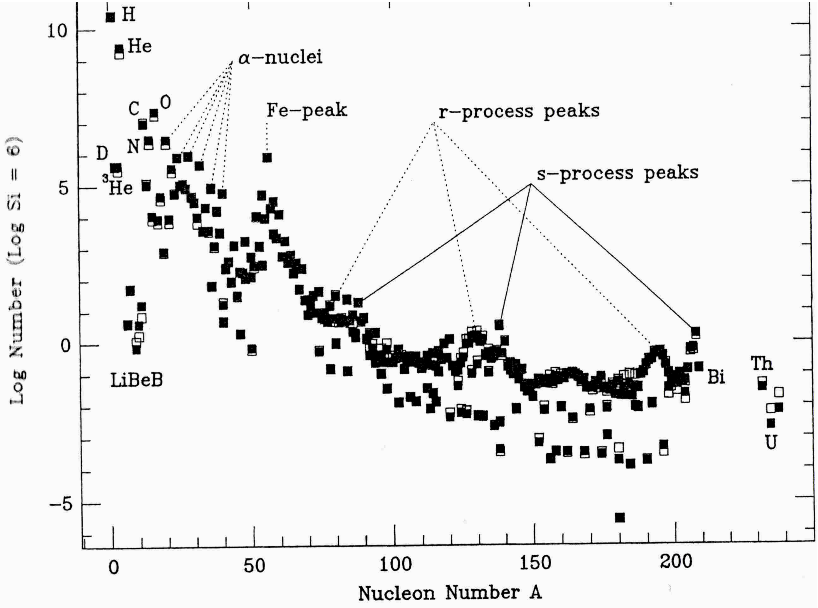
- ν-process
- νp-process

} SN neutrino winds ($A > 56$)

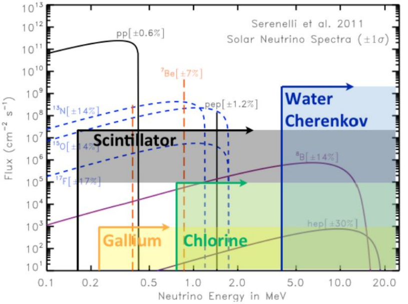
- BBN (H, He, Li)
- Spallation (Li, Be, B, + random isotopes)

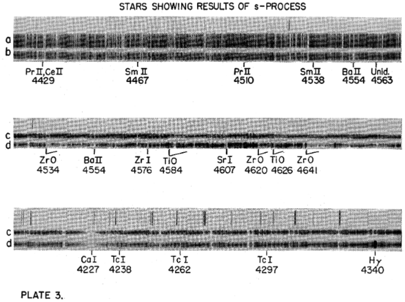
} Non-Stellar Nucleosynthesis

SIGNATURES OF NUCLEOSYNTHETIC PROCESS – SOLAR SYSTEM ABUNDS

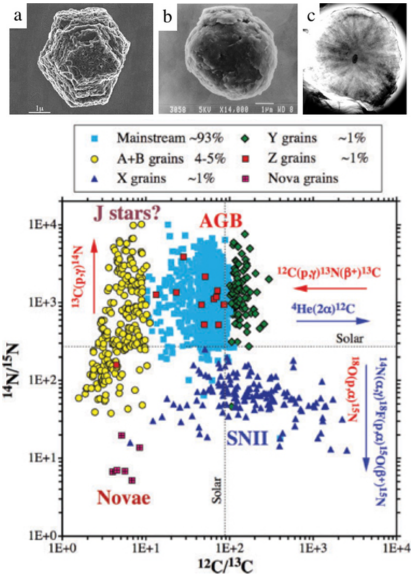


OTHER SIGNATURES OF NUCLEOSYNTHETIC PROCESS



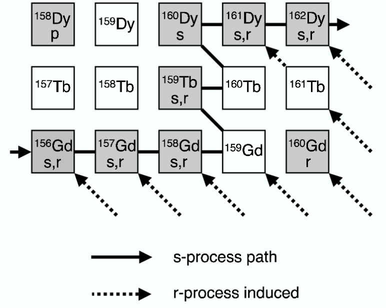


B²FH (1957)



Zinner (2008)

Characterized by their neutron-capture time scales compared to average β-decay half lives.

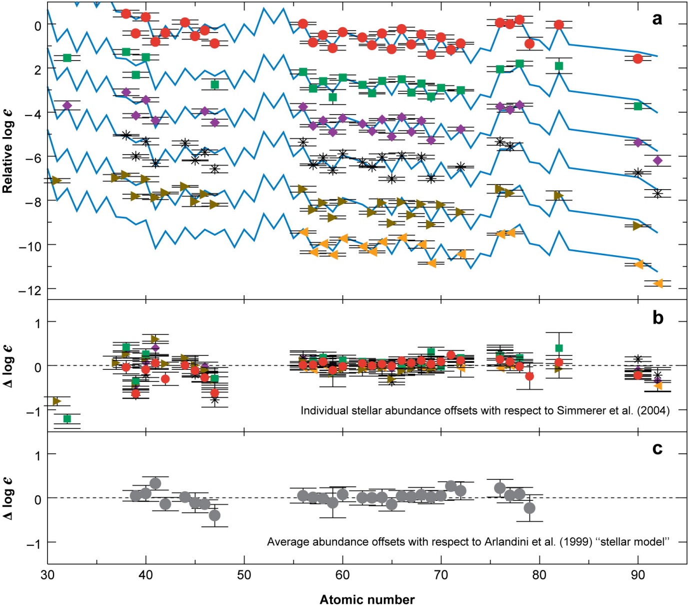


Dy: Dysprosium
Tb: Terbium
Gd: Gadolinium

- The r-process $\tau_\beta >> \tau_{\mathrm{n}}$; $\mathrm{N_n} > 10^{20}$ n/cm^3. Unstable nucleus captures another neutron before decaying. Operates far from stability and decays back.
- The s-process $\tau_\beta << \tau_{\mathrm{n}}$; $\mathrm{N_n} > 10^{7}$ n/cm^3. Unstable nucleus decays before capturing another neutron. Operates close to the valley of β-stability
- If $\tau_\beta \approx \tau_{\mathrm{n}}$ several paths possible (branching point)

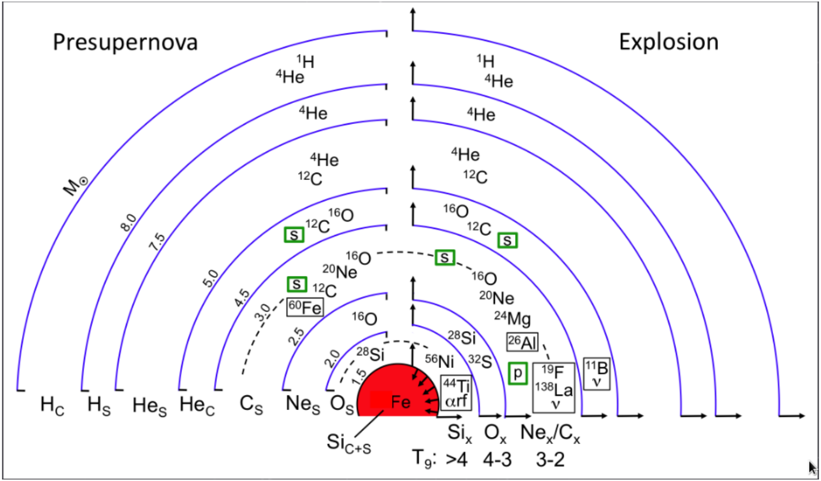
Iliadis (2007)

MULTIPLE SITES/COMPONENTS?



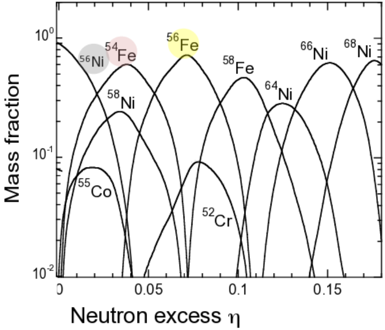
Sneden et al. (2008)

MASSIVE STAR STRUCTURE



José and Iliadis (2011)

NSE timescale: $t_{4GK} = 1\text{hr}$; $t_{6GK} = 10^{-3}\text{s}$



$$Y_e = \sum_i Z_i Y_i = \sum_i \left(\frac{Z_i}{A_i}\right) X_i$$

$$\eta = \sum_i [N_i - Z_i]\, Y_i = \sum_i \left[\frac{N_i - Z_i}{A_i}\right] X_i = \sum_i \left[\frac{A_i - 2Z_i}{A_i}\right] X_i$$

$$\eta = 1 - 2Y_e\,,$$

Assume plasma consists only of:

^{56}Fe η=(N-Z)/M=(30-26)/56=0.07

^{56}Ni η=(N-Z)/M=(28-28)/56=0

^{54}Fe η=(N-Z)/M=(28-26)/54=0.04

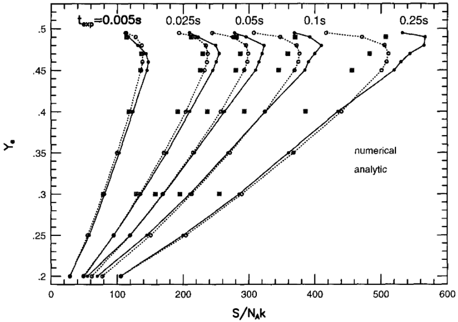
During NSE abundances determined by repeated application of Saha equation

$\longrightarrow N_i(T,\rho,\eta)$

WHY NO R-PROCESS IN MASSIVE STARS?

After NSE the nucleosynthesis depends on three wind parameters that set Y_n/Y_{seed}. In general high entropy, short expansion timescales, and low electron fractions will lead to r-process.

$$S \propto T^3/\rho$$



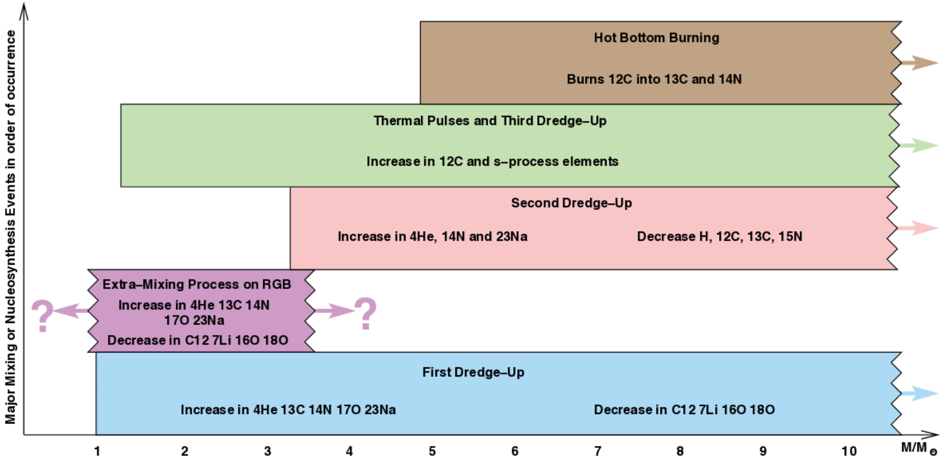
State of the art models suggest:

$\tau \approx 0.01$s, $S/k \approx 100$ in the wind.

Need $S/k \geq 400$ given typical expansion and Ye from the models.

Hoffman et al. (1997)

SURFACE ABUNDANCES AND YIELDS



$$X_{i,\mathrm{Yield}}(\text{Mass Loss, SN explosion}) = X_{i,\mathrm{ejected}} - X_{i,\mathrm{initial}}$$

Karakas and Lattanzio (2014)

NUCLEOSYNTHETIC CONTRIBUTION – SINGLE STARS

Mass Range $\mathrm{M}_\odot$	Main Products	Comments
$\lesssim 0.8$		They lock up gas
[0.8 ,8.0]	^{4}He, ^{12}C, ^{14}N, Fluorine, CNO isotopes and s-process	Differences across masses due to dredge-up events, HBB, etc. S-process from ^{13}C(α,n)^{16}O source
$\gtrsim 10$	(N, C, O, Ne, Mg) (Al, Si, S, Ar, Ca) Fe peak, s-process r- and νp- process p process	Hydrostatic burning phases Hydrostatic and (SN) explosive Essentially explosive burning (NSE, QSE) ^{22}Ne(α,n)^{25}Mg source during core-He and shell-C burning phases. Neutrino winds?
$\gtrsim 100$	Oxygen	And lots of it

NUCLEOSYNTHETIC CONTRIBUTION – DUPLICIT SYSTEMS

System	Main Products	Comments
Nova	^{26}Al, ^{22}Na, ^{15}N, ^{17}O, ^{13}C, ^{7}Li	WD + low-mass companion (typically K-M dwarf), Recurrent.
Type 1a	Fe-peak nuclei, ^{56}Ni (^{56}Fe), possible p-process?	CO WD + companion (SD/DD). Several ignition regimes possible
Type 1 XRB	αp and rp nuclei	NS + low-mass companion. Most frequent type of thermonuclear explosions. Escape?
Hard GRB (Kilonova)	r-process	NS+NS. GW 170817
Soft GRB	^{56}Ni, ^{49}Ti, ^{45}Sc, ^{64}Zn, ^{92}Mo	Rich nucleosynthesis possible from BH/accretion disc channel. Depends on model details especially mass-accretion rate.

MASSIVE STAR YIELD UNCERTAINTIES

TABLE 1

Dependence on Mass Cut: Yield ($M_\odot$)

	Mass Cut (25 $M_\odot$ Model)[a]			Mass Cut (20 $M_\odot$ Model)[b]			
Element	1.42	1.54	1.62	1.42	1.55	1.62	Main Element
Fe.......	2.44E−01	1.62E−01	1.14E−01	1.72E−01	9.53E−02	5.50E−02	^{56}Ni
Cr.......	1.30E−03	1.27E−03	1.24E−03	1.31E−03	1.20E−03	1.14E−03	^{52}Fe
Mn......	3.38E−04	3.37E−04	3.37E−04	3.35E−04	3.34E−04	3.33E−04	^{55}Co
Co	6.87E−04	4.84E−04	3.01E−04	5.33E−04	2.33E−04	7.00E−05	^{59}Cu
Ni.......	8.71E−02	5.48E−02	3.64E−02	6.42E−02	2.70E−02	7.16E−03	^{58}Ni

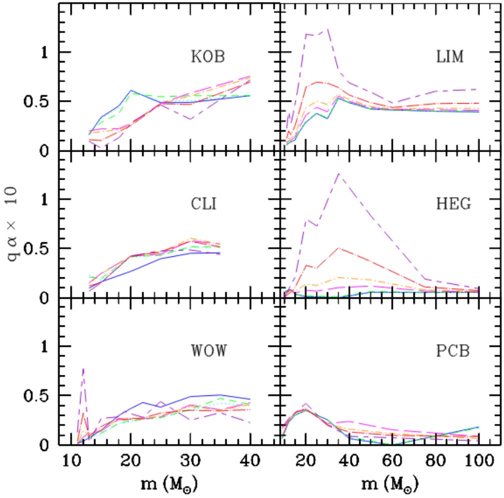
[a] $M_{\rm core} = 8\ M_\odot$, $E_{\rm exp} = 1.0 \times 10^{51}$ ergs, $Y_e^{\rm deep} = 0.4950$.
[b] $M_{\rm core} = 6\ M_\odot$, $E_{\rm exp} = 1.0 \times 10^{51}$ ergs, $Y_e^{\rm deep} = 0.4940$.

$S = k \log \Gamma$: Universe: $S/k \approx 10^{10}$, MS/room: $S/k \approx 10$, SNCC: $S/k \approx 1$

- Mass cut usually taken at S/k=4. Coincides well to first principle models usually around base of the oxygen shell.
- Rotation
- Binarity
- Mass Loss
- Overshoot, semi convection, instabilities, convective boundaries.

Nakamura et al (1999)

MASSIVE STAR YIELDS



- Z=0.0, 0.0001, 0.0004, 0.004, 0.008, 0.02, 0.05
- **WOW** - Wooley and Weaver (1995)
- **PCB** - Portinari, Chiosi Bressan (1998)
- **CLI** - Chieffi and Limongi (2003, 2004)
- **LIM** - Limongi and Chieffi (2006, 2012)
- **KOB** - Kobayashi et al. (2006) + Rauscher et al (2002)
- **HEG** - Heger and Woosely (2010) + Frölich et al (2006)
- See also Pignatari et al. (2015)

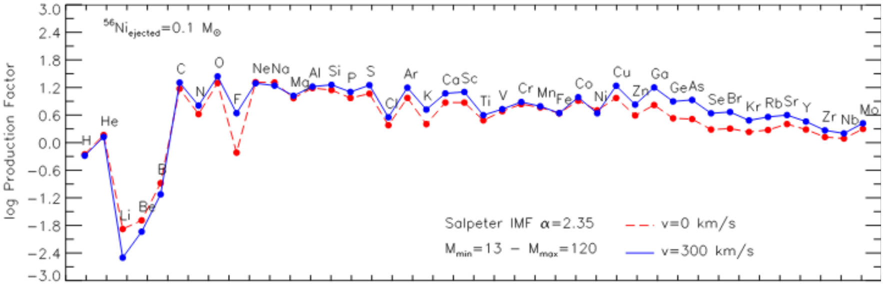
Predictions for α yields at different Z, where $\alpha =^{20}$ Ne $+^{24}$ Mg $+^{28}$ Si $+^{32}$ S $+^{40}$ Ca

Molla et al. (2015)

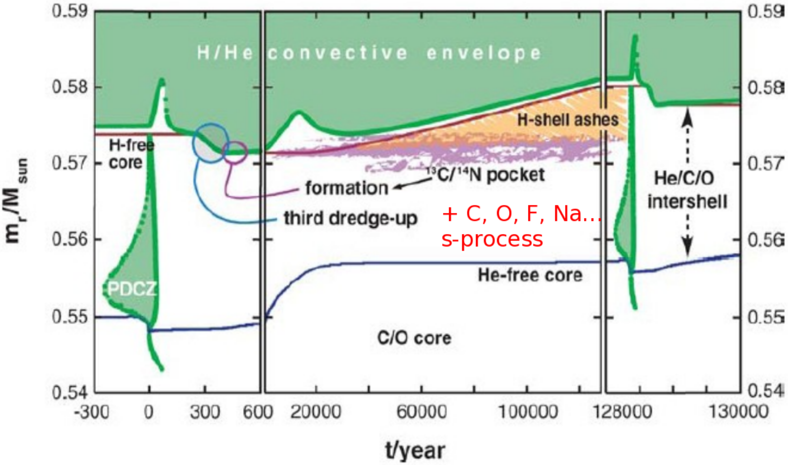
Table 1. Yield definitions

Nuclide i	Yields $Y_i(M)$	Net yields $y_i(M)$	Production factors $f_i(M)$
Created	$> M_{0,i}$	> 0	> 1
Re-ejected	$= M_{0,i}$	$= 0$	$= 1$
Destroyed	$< M_{0,i}$	< 0	< 1

$M_{0,i}$ is defined in Eq. 2.16.



Chieffi and Limongi (2013)

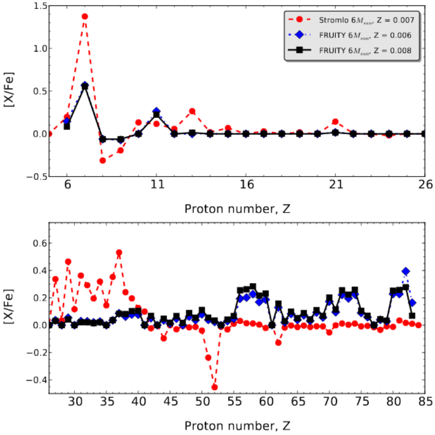


0.59
0.58
0.57
0.56
0.55
0.54
m_r/M_{sun}
H/He convective envelope
H-free core
PDCZ
formation
third dredge-up
$^{13}C/^{14}N$ pocket
H-shell ashes
+ C, O, F, Na...
s-process
He-free core
C/O core
He/C/O intershell
-300
0
300
600
20000
60000
100000
128000
130000
t/year

AGB YIELDS

Reference	Mass range (in $M_\odot$)	Metallicity range (in mass fraction, Z)	s-process?	Downloadable tables?
Fenner et al. (2004)	2.5–6.5	$[Fe/H] = -1.4$	No	No
Herwig (2004b)	2.0–6.0	1×10^{-4}	No	Yes
Karakas & Lattanzio (2007)	1.0–6.0	1×10^{-4}, 4, 8×10^{-3}, 0.02	No	Yes
Campbell & Lattanzio (2008)	1.0–3.0	$Z = 0$, $[Fe/H] = -6.5, -5.45, -4, -3$	No	Yes
Iwamoto (2009)	1.0–8.0	$Z = 2 \times 10^{-5}$	No	No
Karakas (2010)	1.0–6.0	1×10^{-4}, 4, 8×10^{-3}, 0.02	No	Yes
Siess (2010)[a]	7.5–10.5	1×10^{-4} to 0.02	No	Yes
Cristallo et al. (2011)[b]	1.3–3.0	1×10^{-4} to 0.02	Yes	Yes
Ventura et al. (2013)	1.5–8.0	3×10^{-4}, 10^{-3}, 0.008	No	No
Gil-Pons et al. (2013)[c]	4.0–9.0	1×10^{-5}	No	Yes
Pignatari et al. (2013)	1.5, 3.0, 5.0	0.01, 0.02	Yes	Yes
Karakas, Marino, & Nataf (2014)	1.7, 2.36	3, 6×10^{-4}	Yes	Yes
Ventura et al. (2014)	1.0–8.0	4×10^{-3}	No	No
Doherty et al. (2014a)	6.5–9.0	0.004, 0.008, 0.02	No	Yes
Doherty et al. (2014b)	6.5–7.5	0.001, 1×10^{-4}	No	Yes
Straniero et al. (2014)	4.0–6.0	0.0003, $[\alpha/Fe] = +0.5$	Yes	Yes

[a] Yields for six metallicities are provided with the range noted in the table.
[b] Yields for nine metallicities are provided with the range noted in the table.
[c] Downloadable tables are surface abundance predictions, yields are given in their Table 4.



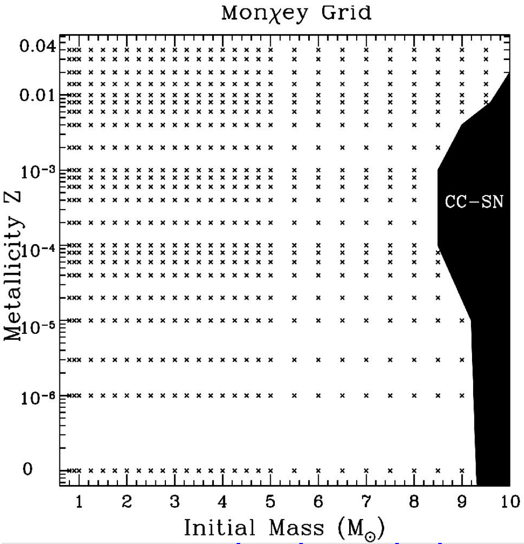
Potential differences and uncertainties in the models

- Mass loss prescription
- Nuclear network strategy
- Treatment of convective boundaries
- Paramterization of C13 pocket and source activation
- Number of thermal pulses and dredge-up efficiency (λ)
- Strength and depth of HBB
- Extra mixing
- PIE/DSF at low Z

Karakas and Lugaro (2016)

The Monash Chemical Yields Project

Doherty, Lattanzio, Angelou, Campbell, Church, Constantino, Cristallo, Gil-Pons, Hampel, Henkel, Lugaro,Karakas,Stancliffe



MonΧey

A large and homogeneous set of (single star) nucleosynthetic yields for low and intermediate mass stars for all elements H-Pb

Grid will consist of over 800 detailed evolutionary and nucleosynthetic models from ~ 0.8 Msun to core collapse supernova boundary (CC-SN) Also will include various test subgrids (ie mass loss rates)

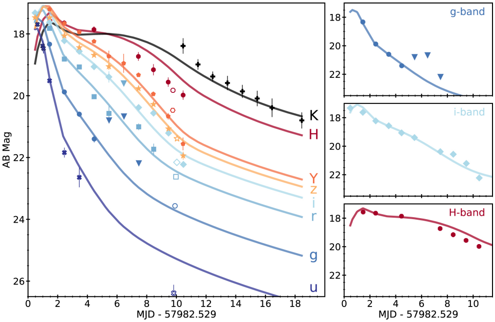
Monχey-web: online tools+data

Coming Soon : Mid 2018 First Release

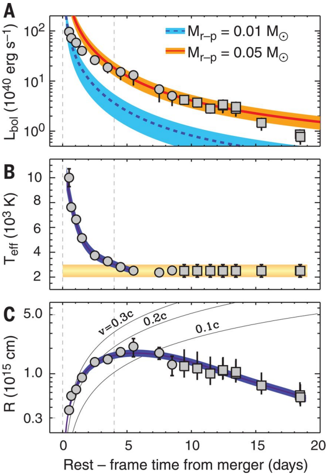
Contact : Carolyn.Doherty @ csfk.mta.hu (Konkoly Observatory - Hungary)

GW170817 + GRB 170817A

- GRB (2s)
- Gravitational waves
- Transient optical/near-infrared source from r-process.



Kasen et al. (2017)

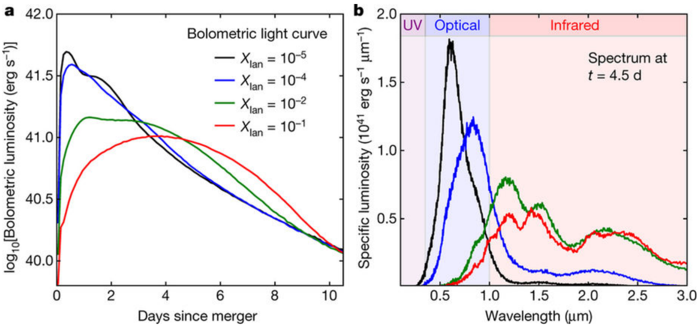


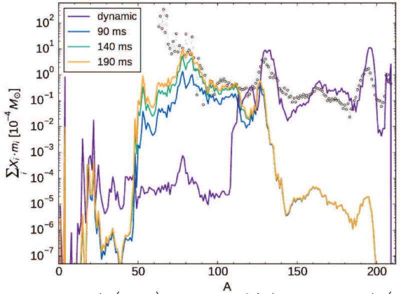
Drout et al. (2017)

Opacities from bound-bound transitions of open f-shell, Lanthanide elements (Nd and Er) responsible for observed emission.

PS: Models suggest <Ye> $\approx$ 0.1, <S/k> $\approx$ 20 (Bovard et al. 2017)

AN R-PROCESS SITE

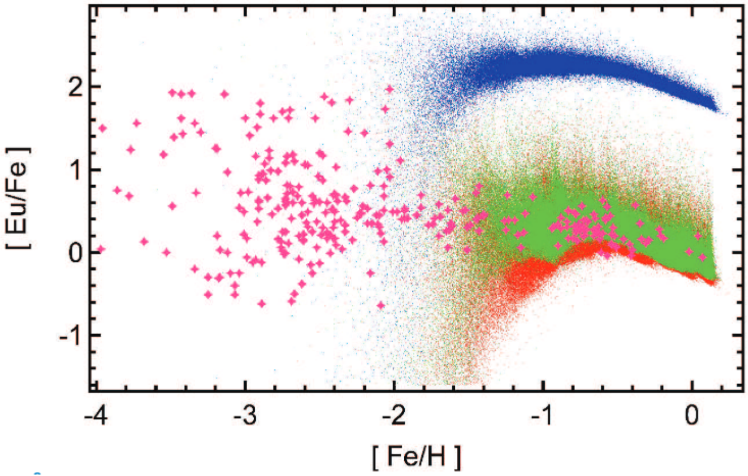




Top:Kasen et al. (2017). Bottom:Thielemann et al. (2017)

- Mass ejected is quite large
- The rate of such events in the Galaxy is quite uncertain.
- I've seen back the envelope that show they can produce all r-process within uncertainty.
- I've also had people tell me that without revising merger rate they over produce Galactic r-process

ANOTHER SITE?

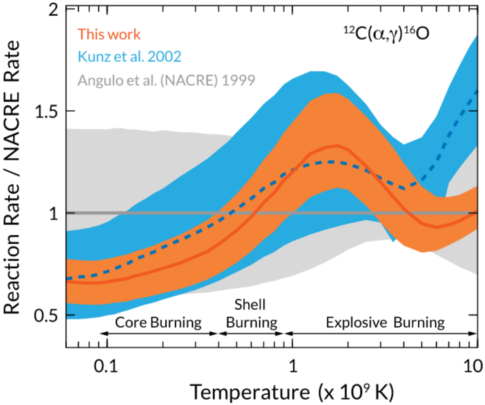


Magenta stars represent observations. Red- CE model star abundances assuming coalescence timescale of 10^8 years, Green assumes 10^6 years, Blue show increase in probability of NS mergers. Within this treatment of galactic chemical evolution, none of these options would permit a fit with observations of low metallicity stars in the metallicity range -4≤[Fe/H]≤-2.5

Thielemann et al. (2017)

(SOME) NUCLEAR PHYSICS UNCERTAINTIES

- Can estimate 3α reaction. But its never been measured in a laboratory: uncertain $\pm 15\%$. Theoretical determinations do not reproduce to fundamental observations.
- $^{12}C(\alpha, \gamma)^{16}O$ we are forced to extrapolate into relevant regime but this is complicated by the existence of two subthreshold levels. Important as this will determine the nature of the remnant neutron star.
- The various measurements of ^{16}O + ^{16}O are in poor agreement at the lower energies. Incomplete knowledge of the branching ratios for the different exit channels. Primary O reactions least a factor of ≈ 3 uncertain. Secondary reactions probably uncertain to within 25%
- Nuclear properties far from stability.



deBoer et al. (2017)

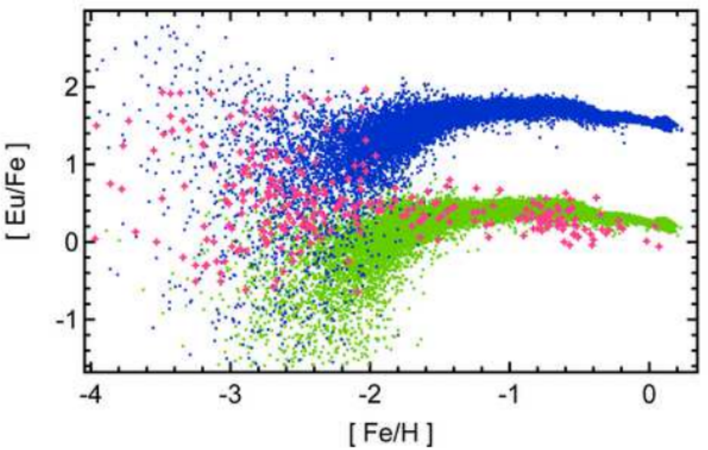
(SOME) OPEN QUESTIONS

- Spite Plateau/ BBN (see J.M talk)
- Role of Mergers/Type 1 XRB?
- Do we now predict an over-production of r-process nuclei? How many sites do we need?
- Do NS-NS mergers occur early enough to explain the UMP stars?
- Do we need other processes (LEPP) to explain all s-process nuclei? νp-process sufficient to explain Sr, Y and Z?
- We have an s/r process. Is there an i-process and what role does it play?
- Are all nuclear physics measurement techniques equal?
- Impact of metallicity on SN1a?
- IMF? (See P.K talk)

APPENDIX

R-PROCESS

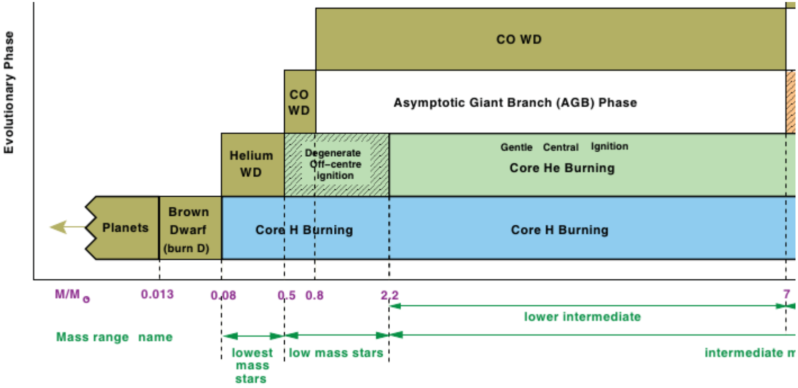
A fraction of high mass stars end their life as a "magneto-rotationally driven supernova" (magnetar) forming in the center a highly magnetized neutron star (with fields of the order 10^{15}G) and ejecting r-process matter along the poles of the rotation axis.



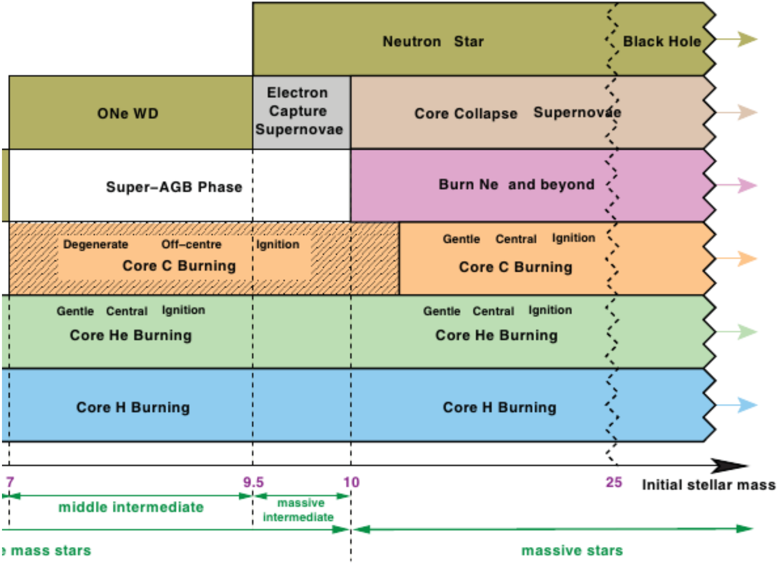
Green: CE model star abundances assuming Jet-SN formation of 0.1%, blue assuming 1% (Wehmeyer et al. 2015)

HYDROSTATIC BURNING PHASES AND REMNANTS

Low & Intermediate Mass Stars



Karakas and Lattanzio (2014)



Karakas and Lattanzio (2014)

MASSIVE STAR BURNING

Central Burning Phase	Main Products	Temperature (K)	Density (g/cc)	Duration
hydorgen burning	He	7×10^7	10	10^7 years
helium burning	C, O	2×10^8	2000	10^6 years
carbon burning	Ne, Na, Mg, Al	8×10^8	10^6	1000 years
neon burning	O, Mg	1.6×10^9	10^7	3 years
oxygen burning	Si, S, Ar, Ca	1.8×10^9	10^7	0.3 years
silicon burning	Fe	2.5×10^9	10^8	5 days

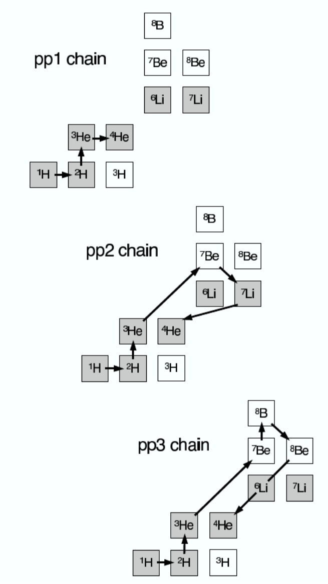
”The late stages (> helium burning) of evolution in massive stars are characterized by huge luminosities, carried away predominantly by neutrinos, and consequently by short time scales. The nuclear physics can become quite complicated.”

– Woosley, Heger, and Weaver (2002) Rev. Mod. Phys., 74, 1016.

NUCLEOSYNTHETIC PROCESSES

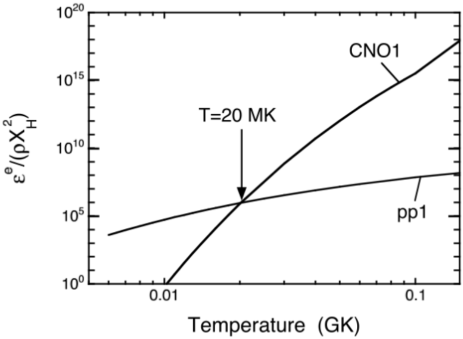
IMAGE CREDITS

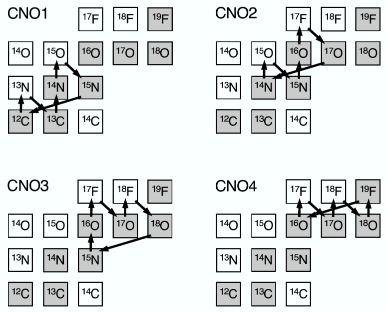
With thanks to Christian Iliadis and his book
Nuclear Physics of Stars (Wiley 2007)



pp1 chain	pp2 chain	pp3 chain
$p(p,e^+\nu)d$	$p(p,e^+\nu)d$	$p(p,e^+\nu)d$
$d(p,\gamma)^3He$	$d(p,\gamma)^3He$	$d(p,\gamma)^3He$
$^3He(^3He,2p)\alpha$	$^3He(\alpha,\gamma)^7Be$	$^3He(\alpha,\gamma)^7Be$
	$^7Be(e^-,\nu)^7Li$	$^7Be(p,\gamma)^8B$
	$^7Li(p,\alpha)\alpha$	$^8B(\beta^+\nu)^8Be$
		$^8Be(\alpha)\alpha$

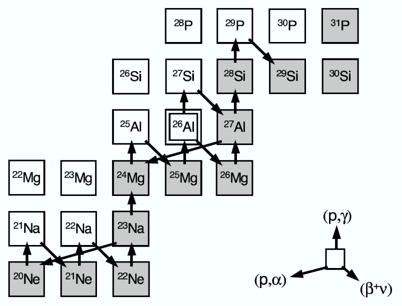
$T_{1/2}$: ^8B (770 ms)





CNO1	CNO2	CNO3	CNO4
^{12}C(p,γ)^{13}N	^{14}N(p,γ)^{15}O	^{15}N(p,γ)^{16}O	^{16}O(p,γ)^{17}F
^{13}N($\beta^+\nu$)^{13}C	^{15}O($\beta^+\nu$)^{15}N	^{16}O(p,γ)^{17}F	^{17}F($\beta^+\nu$)^{17}O
^{13}C(p,γ)^{14}N	^{15}N(p,γ)^{16}O	^{17}F($\beta^+\nu$)^{17}O	^{17}O(p,γ)^{18}F
^{14}N(p,γ)^{15}O	^{16}O(p,γ)^{17}F	^{17}O(p,γ)^{18}F	^{18}F($\beta^+\nu$)^{18}O
^{15}O($\beta^+\nu$)^{15}N	^{17}F($\beta^+\nu$)^{17}O	^{18}F($\beta^+\nu$)^{18}O	^{18}O(p,γ)^{19}F
^{15}N(p,α)^{12}C	^{17}O(p,α)^{14}N	^{18}O(p,α)^{15}N	^{19}F(p,α)^{16}O

$T_{1/2}$: ^{13}N (9.965 min); ^{15}O (122.24 s); ^{17}F (64.49 s); ^{18}F (109.77 min)

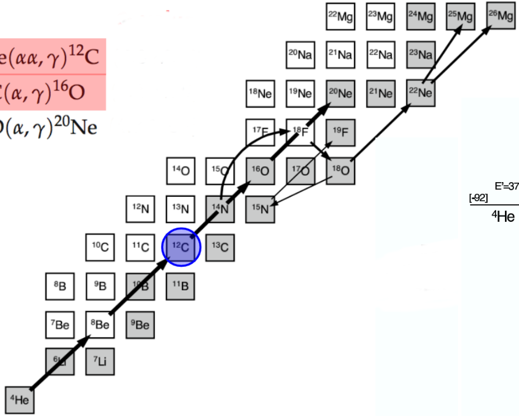


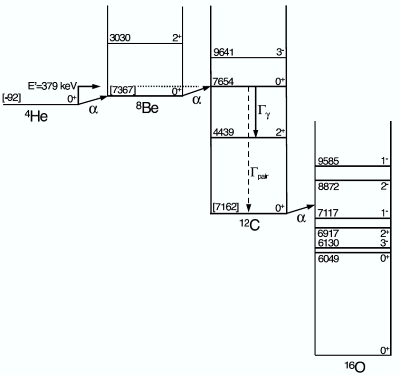
HBB: NeNa $\approx$ 40MK, MgAl $\approx$ 70 MK

$^{4}\mathrm{He}(\alpha\alpha,\gamma)^{12}\mathrm{C}$

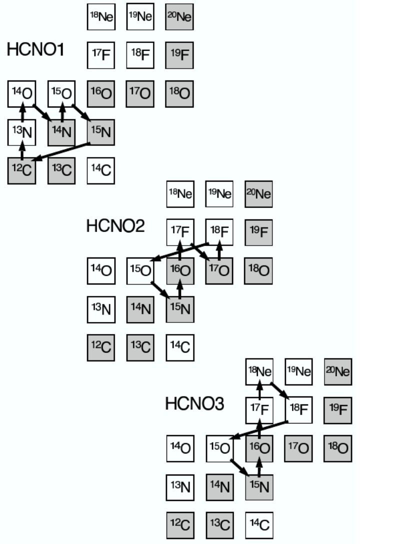
$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

$^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$

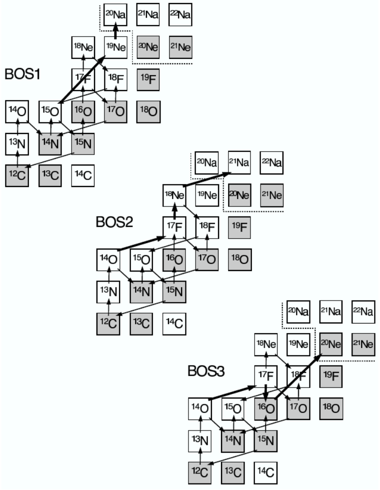




It was pointed out (Hoyle 1954) that the overall conversion of three α-particles to one ^{12}C nucleus during helium burning would be too slow unless the second step proceeds via an s-wave resonance (Jπ = 0 +) corresponding to a compound level near the α-particle threshold in ^{1}2C (Sα = 7367 keV).

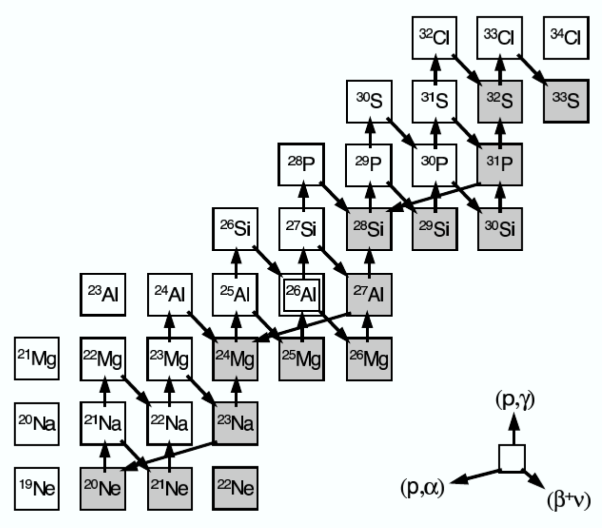


Hot CNO T=100-400 MK. β+ start competing with proton capture. H exhausted after a few thousand seconds.



HCNO Break Out T $>$ 500MK. α-particle captures on O isotopes remove HCNO catalysts.

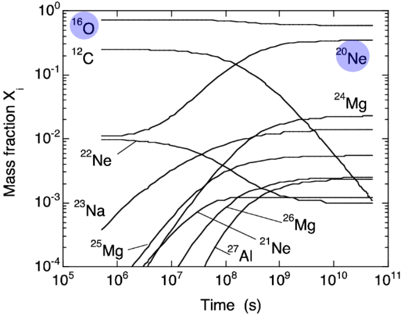
EXPLOSIVE H-BURN A > 20



T $>$ 250 MK. This energy is generated by building up heavier nuclei from lighter seed nuclei via proton-captures and β+ -decays (typical Nova conditions). Once we reach GK (Type 1 XRB) can build up to Ni through rp and αp-processes

Hydrostatic Burning T = 0.61.0 GK
Explosive Burning T = 1.8 – 2.5 GK

- **Primary reactions:**
  $^{12}C(^{12}C,p)^{23}Na$ (Q=2.2 MeV)
  $^{12}C(^{12}C,\alpha)^{20}Ne$ (Q=4.6 MeV)
  $^{12}C(^{12}C,n)^{23}Mg$ (Q=-2.6 MeV
  + several secondary reactions

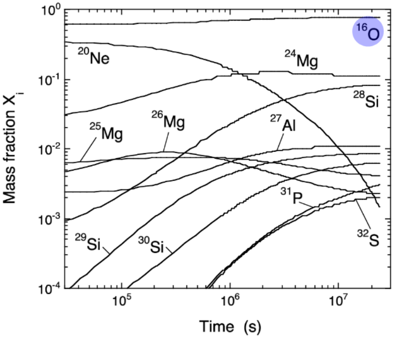


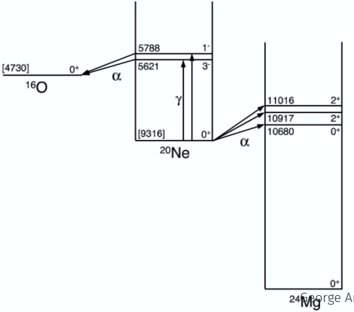
Time integrated abundance flows for conditions typical of core-carbon burning in a $25M_{\odot}$ star.

NEON BURNING

- Hydrostatic Burning
  T= 1.2 – 1.8 GK
- Explosive Burning
  T= 2.5 – 3.0 GK
- Might expect ^{16}O + ^{16}O is the next process to proceed
- Now at temperatures where photodisintegrations play a significant role.

- **Primary reaction:**
  $^{20}Ne(\gamma,\alpha)^{16}O$ (Q=-4730 keV)
- **Secondary reactions**
  $^{20}Ne(\alpha,\gamma)^{24}Mg(\alpha,\gamma)^{28}Si$
  + more



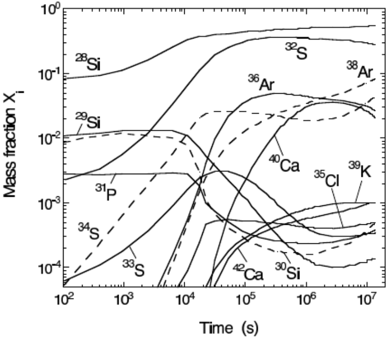


- Hydrostatic Burning T= 1.5 — 2.7 GK
- Explosive Burning T= 3.6 GK
- Primary reactions

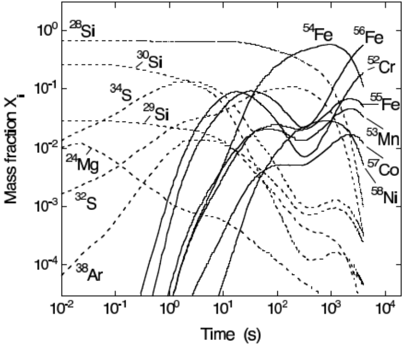
$$^{16}\mathrm{O}(^{16}\mathrm{O},\mathrm{p})^{31}\mathrm{P}$$
$$^{16}\mathrm{O}(^{16}\mathrm{O},2\mathrm{p})^{30}\mathrm{Si}$$
$$^{16}\mathrm{O}(^{16}\mathrm{O},\alpha)^{28}\mathrm{Si}$$
$$^{16}\mathrm{O}(^{16}\mathrm{O},2\alpha)^{24}\mathrm{Mg}$$
$$^{16}\mathrm{O}(^{16}\mathrm{O},\mathrm{d})^{30}\mathrm{P}$$
$$^{16}\mathrm{O}(^{16}\mathrm{O},\mathrm{n})^{31}\mathrm{S}$$

- Plus many secondary
- The reaction rate contributions for the emission of protons ≈ 62%, α-particles ≈21%, and neutrons ≈ 17%.

- Photodisintegration rearrangement & QSE
- A = 24–46 form one large quasi-equilibrium cluster. A second cluster at Fe peak.



- Hydrostatic burning
  T= 2.8 – 4.1 GK
- Explosive burning T= 4 – 5 GK
- Coloumb barrier for ^{28}S+^{28}Si too high
- Many lighter particles liberated through photodisintegration and they combine to form heavier (Fe-peak) nuclei
- Photodisintegration rearrangement on larger scale.



ν- AND νP-PROCESS

ν-process

$$(Z, A) + \nu \rightarrow (Z, A)^* + \nu' \rightarrow (Z, A-1) + n + \nu' ,$$
$$\rightarrow (Z-1, A-1) + p + \nu' ,$$
$$\rightarrow (Z-2, A-4) + \alpha + \nu' .$$

νp -process

$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$
$$\nu_e +^4 \mathrm{He} \rightarrow^3 \mathrm{He} + p + e^-$$
$$\bar{\nu}_e +^4 \mathrm{He} \rightarrow^3 \mathrm{H} + n + e^+$$

sequence of (p,γ) and (n,p) or β^+ reactions producing neutron-deficient nuclei with A > 64.

TABLE 25

SUMMARY TABLE: SPECIES DUE TO NEUTRINO NUCLEOSYNTHESIS[a]

Species	H	He	C	Ne	O	NSE
^{7}Li	B	A	C	...	...	A
^{10}B	...	C	B	...	...	...
^{11}B	...	B	A	...	...	A
^{15}N	...	...	C	C	C	...
^{19}F	...	...	...	A	...	...
^{22}Na	...	...	...	E	...	...
^{26}Al	...	...	...	E	...	...
^{27}Al	...	...	...	...	C	...
^{31}P	...	...	...	...	E	...
^{35}Cl	...	...	...	E	E	...
^{39}K	...	...	...	...	E	...
^{40}K	...	...	...	E	B	...
^{41}K	...	...	...	...	E	...
^{43}Ca	...	...	...	C	C	...
^{45}Sc	...	...	...	...	C	B
^{47}Ti	...	...	...	C	C	C
^{49}Ti	...	...	...	...	...	B
^{50}V	...	...	...	E	B	B
^{51}V	...	...	...	C	E	E
^{55}Mn	...	...	...	...	...	E
^{59}Co	...	...	...	...	...	E
^{63}Cu	...	...	...	...	...	B
^{138}La	...	...	...	A	...	...
^{180}Ta	...	...	...	A	...	...

[a] A = species produced in full abundance; B = important production; C = minor production; E = enhanced significant production.

Woosley et al. (1990), Fröhlich et al. (2006)

TYPE 1A SUPERNOVA

W7 - Nomoto et al. (1984) 1D deflagration. Compared here to 2D models with (a) deflagration, (b) Centre-delayed and (c) Off-Centre delayed detonation.

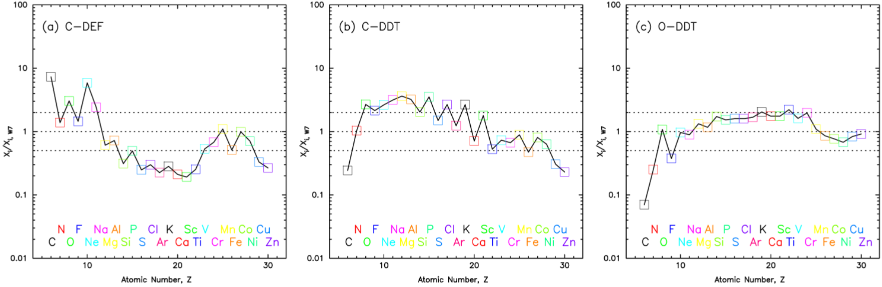


Figure 14. Ratios of integrated element yields to the W7 model yields.

- **Prompt Detonation** – Pure detonation propagating from the centre (cannot reproduce distribution of intermediate-mass elements from spectra)
- **Deflagration** – Subsonic flame allows layers to expand (cannot reproduce Fe peak, energies for majority + other issues)
- **Delayed Detonation** – Deflag front propagates and pre-expands layers before switching to detonation (matches spectroscopic elemental abundances and velocities)

See also Travalio et al (2011) for p-process, Seitenzahl et al. (2013) for 3D yields

Maeda et al. (2010)

Type 1XRB

- 3α process creates ^{12}C
- Accreted material from LM companion allows for rp process (Series of (p,γ) reactions and β^+ decays .
- Also sequence of (α, p) and (p,γ) reactions.
- Reach nuclei far from stability, close to proton drip line.
- Waiting points, i.e. (α,p) reactions cannot progress and must wait for β^+ decay), can affect the nucleosynthetic path and energy output.

Massive Thorn-Zytkow Objects

- Neutron star core surrounded by a large and diffuse envelope (M > 12)
- Convective envelope with turn over of 0.01s
- Material may repeatedly random walk to the base of the convective envelope, spells or rp-conditions separated by intervals long enough for beta decay back towards stability hence interupted rp-process
- Back of envelope suggest that If they exist they could account for all the p-nuclei however do not give solar system abundance pattern

Table 5. Some characteristics of presolar silicon carbide populations

Designation	Mainstream	X	Y	Z	A+B [a]	Nova
Crystal type	3C, 2H [b]	3C, 2H [b]	3C, 2H [b]	3C, 2H [b]	3C, 2H [b]	3C, 2H? [b]
Heavy trace elements [c]	~10-20× [c]	highly depleted	~ 10× [c]	NA	solar or 10-20× [c]	NA
$^{12}C/^{13}C$	10 – 100	20 – 7000	140 – 260	8 – 180	< 3.5 (A) 3.5 – 10(B)	< 10
$^{14}N/^{15}N$	$50 – 2\times10^4$	10 – 180	400 – 5000	$1100 – 1.9\times10^4$	$40–1.2\times10^4$	< 20
$^{29}Si/^{28}Si$ [c]	0.95-1.20×	^{28}Si-rich	0.95-1.15×	≈solar	1.20×	≈solar
$^{30}Si/^{28}Si$ [c]	0.95-1.14×	^{28}Si-rich	^{30}Si-rich	^{30}Si-rich	1.13×	^{30}Si-rich
$^{26}Al/^{27}Al$	10^{-3} to 10^{-4}	0.02 to 0.6	similar to MS	similar to MS	<0.06	up to 0.4
Other isotopic markers [c]	excess in ^{46}Ti, ^{49}Ti, ^{50}Ti over ^{48}Ti	^{44}Ca excess ^{41}K excess	excess in ^{46}Ti, ^{49}Ti, ^{50}Ti over ^{48}Ti	excess in ^{46}Ti, ^{47}Ti, ^{49}Ti over ^{48}Ti	excess in ^{46}Ti, ^{49}Ti, ^{50}Ti over ^{48}Ti	^{47}Ti-rich
^{22}Ne [d]	yes	NA	NA	NA	NA	NA
Abundance	87-94%	1%	1 – 2%	0 – 3%	2 – 5%	<< 1%

Sources: Amari et al. 2001a,b, Hoppe and Ott 1997, Hoppe and Zinner 2000, Nittler and Hoppe 2004a,b,Ott 2003, Zinner 1998

[a] Group A and B grains were initially separated but later found to form a continuum in composition.

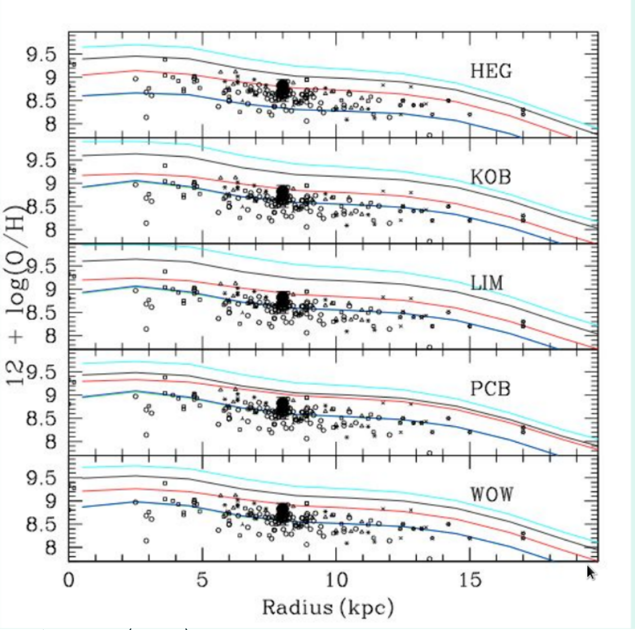
[b] cubic 3C, hexagonal 2H; Daulton et al. (2002, 2003).

[c] Abundance compared to solar composition.

[d] ^{22}Ne = Ne-E(H) = Ne(G); and NA: not analyzed.

COMPONENTS

- Main s-process ($90 < A < 208$) in LIM during TP-AGB with the main neutron source being ^{13}C(α,n)^{16}O reaction
- Weak s-components (A leq 90) in massive stars during core He- and shell C-burning phases with the main source ^{22}Ne(α,n)^{25}Mg reaction.
- Strong s-component, introduced by Clayton Rassbach (1967) in order to reproduce more than 50% of solar ^{208}Pb,. Active in low-Z low-mass AGB stars (≤1.5$M_{\odot}$ Gallino et al. 1998, see also Kappeler et al. 2011 for a recent review)
- Extant chemical evolution models underestimate the Galactic production of Sr, Y and Zr as well as the Solar System abundances of s-only isotopes with $90 < A < 130$. To solve this problem, an additional (unknown) process has been invoked, the so called LEPP (Light Element Primary Process, see Travaglio et al. 2004) The ratio of neutron source/seed nuclei is key



Mollá et al. (2012)

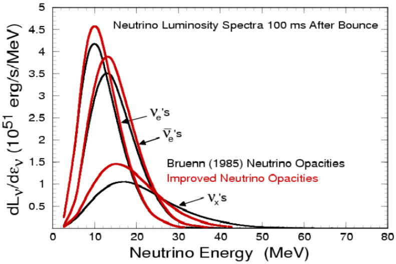
- Salpeter 1995
- Miller Scalo 1979
- Ferrini et al. 1998
- Kroupa 2002
- Chabrier 2003

SUMMARY

- Stellar nucleosynthesis seeks to understand the origin of the isotopes.
- We must consider binaries and single stars. Some systems require multidimensional modelling.
- There are uncertainties from the stellar modelling and nuclear physics.
- To understand the contribution to GCE, the yields need to be integrated over an IMF which is yet another source of uncertainty.
- The best way to quantify the uncertainty is to systematically compare GCE calculations with different yields and IMFs.
- There are still many open questions.

WHY NO R-PROCESS IN MASSIVE STARS?

-
  - The entropy per baryon (S)
  - The expansion timescale (τ)
  - The electron fraction (Y_e or η)



Entropy For radiation dominated environments : $S \propto T^3/\rho$

- $\uparrow$T, $\uparrow$S.
- Photodisintegration destroy seed nuclei $\rightarrow \uparrow Y_n/Y_{seed}$

The expansion timescale $\uparrow \tau$, the less time remains to form seed nuclei.

$$Y_{e,eq} \simeq \frac{\lambda_{\nu_e}}{\lambda_{\nu_e} + \lambda_{\bar{\nu}_e}}$$

$Y_e < 0.5 \rightarrow$ neutron rich

For successful r-process we want high entropy, short expansion timescales, and low electron fractions.

- Entropy too low, $\lambda_{\bar{\nu}_e}$ too low