Understanding Massive Stars: Evolution and Nuclear Burning Stages, Supernova Explosion Mechanism(s), Nucleosynthesis Ejecta, and their Impact on Chemical Evolution

Project Leaders
MASCHE

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IPs and APs and Interest Groups
(in alphabetical order)

University of Basel
*Observations, covered in Roland's talk
Clemson University, North Carolina
GSI/TU Darmstadt, GSI/U. Frankfurt, GSI/U. Giessen
ATOMKI Debrecen
TU Dresden/ FZ Rossendorf
MPIs Garching (MPE*)
MPI for Nuclear Physics Heidelberg
University of Keele
Kocaeli University
Excellence Cluster Munich/Garching (including TU, ESO*)
IAP Paris
IASF Rome
University of Stockholm*
Trieste Observatory
U of Vienna
Nuclear Physics Input

**Experiment:**
- Fusion reactions for stellar evolution and s-process (Dresden: Bemmerer, Zuber; Debrecen: Fülöp, Gyürky; GSI/F: Heil, Reifarth...
  Dresden and Debrecen connection to LUNA)
- Explosive Burning, p-Process, r-process, properties far from stability (especially mass determinations and fission barriers) (Debrecen; GSI: Kelic; GSI/G: Dillmann; Kocaeli: Ozkan, Guray; TU Munich: Bishop; MPI Heidelberg: Blaum, Litvinov
  Kocaeli connection to JINA) – also Wallner & Vockenhuber

**Theory:** (Masche and CoDustMas)
- Prediction of reaction cross section and rates, optical potentials, level densities, giant resonances, fission properties (Basel: Rauscher, FKT; GSI/TUD: Martinez-Pinedo + group, connection to EXNUC and NAVI)
- weak interactions (GSI: Martinez-Pinedo + group)
- nuclear EoS (GSI: Typel, Basel: Hempel, connection to ESF network COMPSTAR)
Stellar Evolution

Stellar Evolution Codes:

FRANEC (historically Frascati)
Rome: Chieffi, Limongi – through all phases of stellar evolution up to collapse

GENEVA Code
Keele: Hirschi – with connections to Geneva (Maeder, Meynet ..), Basel: Frischknecht - through all burning stages, with rotation

MESA Code
Basel: Pignatari; Battino - through all burning stages

*influence on final outcome via treatment of convective mixing and mass loss, stellar winds (connection to CoDustMas), rotation, metallicity, magnetic fields, reaction cross sections, e-capture in late burning stages*
Goal: understand differences among different evolutionary codes. => found an excellent fit between the Geneva and the FRANEC code but only for the extremely simple case of radiative H burning (i.e. by dropping the mixing in the convective core)
But, full and detailed comparison too time consuming!

Main sequence H-burning phase for 20 Msol star

But, full and detailed comparison too time consuming!

Less demanding task:
show, describe (instead of full understanding) the comparison among different codes and just try to discuss the probable reason of the differences. Keele is continuing this task for all late burning stages.
Brief Summary of Burning Stages (Major Reactions)

1. Hydrogen Burning
   pp-cycles -> $^1\text{H}(p, e^+ \nu)^2\text{H}$
   CNO-cycle -> slowest reaction $^{14}\text{N}(p, \gamma)^{15}\text{O}$

   T = (1-4) x 10^7K

2. Helium Burning
   $^4\text{He} + ^4\text{He} \leftrightarrow ^8\text{Be}$
   $^{14}\text{N}(\alpha, \gamma)^{15}\text{O}$

   T = (1-2) x 10^8K

3. Carbon Burning
   $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$
   $^{12}\text{C}(^{12}\text{C}, p)^{23}\text{Na}$

   T = (6-8) x 10^8K

4. Neon Burning
   $^{20}\text{Ne}(\gamma, \alpha)^{16}\text{O}$
   $^{20}\text{Ne}(\alpha, \gamma)^{24}\text{Mg}[(\alpha, \gamma)^{28}\text{Si}]$

   T = (1.2-1.4) x 10^9K

5. Oxygen Burning
   $^{16}\text{O}(^{16}\text{O}, \alpha)^{28}\text{Si}$
   $\ldots, p^{31}\text{P} \ldots, n^{31}\text{S}(\beta^+)^{31}\text{P}$

   T = (1.5-2.2) x 10^9K

6. “Silicon” Burning
   (all) photodisintegrations and capture reactions possible
   $\Rightarrow$ thermal (chemical) equilibrium

   T = (3-4) x 10^9K

Ongoing measurements of key fusion reactions at low energies; neutron sources and sinks, and s-process n-capture cross sections (Dresden, Debrecen, GSI/Frankfurt)

proton/nucleon Ratio Ye decreases with enrichment of metals!!
Constraining Nuclear Physics with stellar evolution:
$^{12}\text{C}^{12}\text{C}$ rate, $3\alpha$

- Full massive star models + post-processing using MPPNP (www.nugridstars.org)

Impact study:
- $\text{C}12+\text{C}12\alpha,p,n$ channels
- s-process, p-process
  (including production of Mo92-94,Ru96-98)

**Bennett et al. 2012, MNRAS**
Impact study on different masses using different $\text{C}12+\text{C}12$ rates

See Suda et al 2011 for a study constraining $3\alpha$ reaction
rotation produces primary nitrogen and later $^{22}\text{Ne} \Rightarrow$ enhances mass loss and s-process source
s-Processing in rotating low-metallicity stars, $Z = 10^{-5}$

Connection to chemical evolution, Chiappini et al. (2011) FirstStars

**Fig. 1.** Overproduction factors (abundances divided by their initial values) for the $25 \, M_\odot$ models with $Z = 10^{-5}$ after the end of core He-burning. The model without rotation (triangles) does not produce s-process efficiently whereas the rotating models (filled circles, B1 and diamonds, B3) produce significant quantities of s-process. The additional rotating models with reduced $^{17}\text{O}(\alpha, \gamma)$ rates (B4, CF88/10) highlights the uncertainty linked to the neutron poison $^{16}\text{O}$.

Dependence on rotation and $^{16}\text{O}$ neutron poison via $^{16}\text{O}(n, \gamma) ^{17}\text{O}(\alpha, \gamma)$ or $^{17}\text{O}(\alpha, n)$ (Frischknecht, Hirschi, Thielemann 2012) still unclear, Görres (2012) vs. Fulton (2013)
Simulations of Core Collapse SNe

1-2-3D simulations with rotation and magnetic fields:
Liebendörfer et al (Basel),
Fischer (GSI/TUD)
Janka et al. (MPA Garching)

Nuclear Input:
GSI/TUD (weak interactions, Martinez-Pinedo;
    EoS, Typel)
Basel     EoS, Hempel + COMPSTAR)

Reaction rates and nucleosynthesis:
Basel (Rauscher, Pignatari, Thielemann),
GSI/TUD (Martinez-Pinedo et al., Arcones)

Questions: What is the site of the r-process, p-process? How far reaches the \(\nu\)p-process? How much mass is ejected in radioactive elements?
Supernovae in 1D

SN Simulations: \[ M_{\text{star}} \sim 8...10 \, M_{\odot} \]

"Electron-capture supernovae" or "ONeMg core supernovae"

- No prompt explosion!
- Mass ejection by "neutrino-driven wind" (like Mayle & Wilson 1988 and similar to AIC of WDs; see Woosley & Baron 1992, Fryer et al. 1999; Dessart et al. 2006)
- Explosion develops in similar way for soft nuclear EoS (i.e. compact PNS) and stiff EoS (less compact PNS)


Convection is not necessary for launching explosion but occurs in NS and in neutrino-heating layer

Fischer et al. 2010
Growing set of 2D CCSN Explosions
(here Hanke & Janka 2013 – MPA Garching)

But 3D still somewhat open!

Positions of shock radii
Simulations in 3D

Finally multi-D core collapse supernovae calculations lead to explosions! (see T. Janka, A. Mezzacappa, C. Ott, etc.; here the Basel version).

There are two transitions: (i) $8-10 M_{\odot}$ progenitors even explode in spherical symmetry, (ii) from regular core collapse SNe with neutron star formation - to faint SNe with fall back and BH formation - BH formation and hypernovae???
Core Collapse Supernovae

- Explosive nucleosynthesis from “induced“ explosion calculations
- The p-process
- The Supernova Mechanism and the innermost ejecta
- The role of neutrinos for the (early) innermost ejecta (the $\nu_p$-process)
- The late neutrino wind
- Passing through the IMF
Explosive Burning

typical explosive burning process timescale order of seconds: fusion reactions (He, C, O) density dependent (He quadratic, C,O linear) photodisintegrations (Ne, Si) not density dependent
Explosive Si-Burning above a critical temperature destroys (photodisintegrates) all nuclei and (re-)builds them up during the expansion. Dependent on density, the full NSE is maintained and leads to only Fe-group nuclei (normal freeze-out) or the reactions linking $^4$He to C and beyond freeze out earlier (alpha-rich freeze-out).
Products of explosive burning (20Msol star)

Results from “thermal bomb“ energy deposition in progenitor model (Nomoto-style)

Fe-group composition depends on $Y_e$ and entropy (alpha-rich freeze-out)

(explosive Si-burning (alpha-rich, incomplete), O-burning, Ne-burning)
Constraining the ejecta from old CCSN explosions with the isotopic signature of presolar grains

- Pignatari et al. 2013, ApJL: SiC-X and LD graphites as tracers of the high velocity of the CCSN shock, carrying the signature of the C-rich C/Si zone, at the bottom of the He/C zone.

- Pignatari et al. 2013, arXiv: SiC-C grains, carrying the signature of the Neutron density in the explosive C-rich He-burning shell. S32-rich grains from the decay of the radioactive Si32.

Connection CoDustMas
Rapp et al. (2007), following p-(gamma)-process calculations within the framework of Rayet et al. (1995) for a 25M_sol star of Yoshida et al. (2002) to verify the impact of nuclear uncertainties.
Comparison with solar p-only nuclei

Goriely & Arnould (2003)

Rapp et al. (2007)

Dillmann et al.
(GSI/UG)

variation of rate uncertainties
Ideas for solutions

There have been many investigations in p-process related reactions (Gyürky, Fülöp, Hasper, Kiss, Yalcin, Mohr, Sonnabend, Dillmann, Rauscher..) which led to improved understanding of alpha and proton optical potentials, but the problem seems not to be solved by nuclear rate uncertainties. The major difficulty is to produce the low-mass Mo and Ru isotopes, which also have a higher abundance than the typical 1% fraction of p-isotopes for heavier elements.

Possible solutions:
analyze environments which start with a different seed composition being then exposed to the photon flux
(a) extent of prior s-processing as possibly found in the accreted He-burning layers of SNe Ia, Howard et al. 1991, Kusakabe et al. 2009, Travaglio et al. 2010, but not a solution for LEPP elements at low metallicities!
will be followed by Pignatari+Battino (Basel)
(b) change evolution of massive stars (e.g. $^{12}$C+$^{12}$C) which changes extent of s-processing before core collapse supernova explosion,
see previous slide Pignatari (Basel)
(c) invent different environment with capture reactions for light p-isotopes. e.g. vp-process, ”weak r-process” (charged particle process)
(see below)
Despite the fact that these nuclear uncertainty tests and experiments (Debrecen, Kocaeli, Dillmann-GSI/UG, Rauscher-Basel) did not lead to a solution of the light p-nuclei problem, they were of immense importance for an improved understanding of charged-particle nuclear reactions with heavy nuclei!!!!!!!!! and also led to.... (Rauscher 2013)

**Resolving the long-standing mystery of alpha-potentials for heavy nuclei**  
**Impact of low-energy Coulex on 144Sm(α,γ)**

**Utilizing standard alpha-potentials is ok!**  
**If Coulomb excitations are included**

- First 2+ at 1.66 MeV
- B(E2)=0.262

- Sensitivity check!
- Above 12 MeV:
  - γ-width
  - neutron width
How to invoke induced explosions for nucleosynthesis purposes?

without a self-consistent mechanism nucleosynthesis can only be calculated with induced explosions. Woosley & Heger position a piston with $1.2\,B$ at $S=4k_B\,/\,b$, Nomoto/Umeda/Thielemann applied thermal bomb and integrate from outside until expected $^{56}\text{Ni}$-yield.
Nucleosynthesis problems in “induced” piston or thermal bomb models utilized up to present to obtain explosive nucleosynthesis yields with induced explosion energies of $10^{51}$ erg

prior results made use of initial stellar structure (and $Y_e$!) when inducing artificial explosion. This neglects the effect of the explosion mechanism on the innermost zones, causes strange overproductions of Ni isotopes and does not go much beyond Ni!

Two aspects:
(i) even in spherical symmetry neglecting neutrinos $\rightarrow Y_e$
(ii) multi-D

high alpha-abundance prefers alpha-rich nuclei ($^{58}$Ni over $^{54}$Fe),

$Y_e$ determines Fe-group isotopes.
PISNe yields, too large odd-even Z scatter, not observed in low metallicity stars

In exploding models matter in innermost ejected zones becomes proton-rich ($Y_e > 0.5$) if the neutrino flux is sufficient (scales with $1/r^2$)!

$Y_e$ dominantly determined by $e^\pm$ and $\nu_e$, $\bar{\nu}_e$ captures on neutrons and protons

\[
\nu_e + n \leftrightarrow p + e^-
\]

\[
\bar{\nu}_e + p \leftrightarrow n + e^+
\]

- high density / low temperature → high $E_F$ for electrons → e-captures dominate → n-rich composition
- if el.-degeneracy lifted for high T → $\nu_e$-capture dominates → due to n-p mass difference, p-rich composition
- in late phases when proto-neutron star neutron-rich, $\nu_e$ see smaller opacity → higher luminosity, dominate in neutrino wind → neutron-rich ejecta

If neutrino flux sufficient to have an effect (scales with $1/r^2$), and total luminosities are comparable for neutrinos and anti-neutrinos, only conditions with $E_{av,\nu} - E_{av,\bar{\nu}} > 4(m_n - m_p)$ lead to $Y_e < 0.5$!
Improved Fe-group composition

Models with $Y_e > 0.5$ lead to an alpha-rich freeze-out with remaining protons which can be captured similar to an rp-process. This ends at $^{64}$Ge, due to (low) densities and a long beta-decay half-life (decaying to $^{64}$Zn).

This effect improves the Fe-group composition in general (e.g. Sc) and extends it to Cu and Zn!

Fröhlich et al. (2004, 2006a), see also Pruet et al. (2005), but see also Izutani & Umeda (2010) for hypernova conditions; main question: which fraction of massive stars have to become hypernovae in order to produce solar Zn???
A new process, which could solve some observational problems of Sr, Y, Zr in early galactic evolution and the problem of light p-process nuclei. Anti-neutrino capture on protons provides always a small background of neutrons which can mimic beta-decay via (n,p)-reactions.

Fröhlich et al. (2006b); also strong overabundances can be obtained up to Sr and beyond (light p-process nuclei) see also Pruet et al. (2006), Wanajo (2006).

Recent analysis by Wanajo et al. (2010, MPA Garching), Arcones et al. (2011, Basel/GSI/TUD) with variation of neutron star masses and reverse shock position
Radioactivity Diagnostics of SN1987A: $^{56}$Ni/Co, $^{57}$Ni/Co, $^{44}$Ti

Leibundgut (ESO) & Suntzeff 2003, other determinations (e.g. $^{44}$Ti undertaken by Fransson+ Stockholm)

total/photon decay energy input from models
Impact on Chemical Evolution of Galaxies

Present nucleosynthesis predictions (pistons or thermal bombs) cannot correctly describe the ejecta of the innermost zones which are affected by the explosion mechanism (e-captures and neutrino interactions → Ye).

Two (still spherically symmetric) approaches with full collapse calculations and approximations for neutrino heating (PUSH – Basel-Darmstadt-Raleigh/NC, Liebendörfer, Perego, Ebinger, Hempel, Casanova, Fröhlich; Neutrino-Driven-Supernovae - Darmstadt, Garching, Ugliano, Arcones, Janka) are on the way to improve that part and predict nucleosynthesis ejecta which include an improved treatment for the innermost ejected zones.

This will permit improved chemical evolution modeling!

N. Prantzos, IAP
F. Matteucci, Trieste
F. Primas, ESO
F. Chiappini, Geneva/Potsdam → First Stars
What is the site of the r-process?

SN neutrino wind, problems: high enough entropies attained? neutrino properties???
Possible Variations in Explosions and Ejecta

- regular explosions with neutron star formation, neutrino exposure, νp-process.
- How to obtain moderately neutron-rich neutrino wind and weak r-process or more ?? (see e.g. Arcones & Montes 2011, Roberts et al. 2010, Arcones & Thielemann 2013)
- under which (special?) conditions can very high entropies be obtained which produce the main r-process nuclei?

Izutani et al. (2009)
Long-term evolution up to 20s, transition from explosion to neutrino wind phase

**Fischer et al. (2010)**

these findings see a longterm proton-rich composition, late(r) transition to neutron-rich ejecta possible?
Inclusion of medium Effects, potential U in dense medium
Martinez-Pinedo et al. 2012, see also Roberts et al., Roberts & Reddy 2012

\[ E_i(p_i) = \frac{p_i^2}{2m_i^*} + m_i + U_i, \quad i = n, p \]

\[ E_{\nu_e} = E_{e^-} - (m_n - m_p) - (U_n - U_p) \]
\[ E_{\bar{\nu}_e} = E_{e^+} + (m_n - m_p) + (U_n - U_p) \]

Can reduce slightly proton-rich conditions (Ye=0.55) down to Ye=0.4!

FIG. 1. (Color online) Opacity and emissivity for neutrino (left panels) and antineutrino (right panels), evaluated at conditions \( \rho = 2.1 \times 10^{13} \text{ g cm}^{-3}, T = 7.4 \text{ MeV} \) and \( Y_e = 0.035 \).
Individual Entropy Components

Farouqi et al. (2010), above $S=270-280$ fission back-cycling sets in such high entropies apparently not obtained!!!

$HEW, ETFSI-Q, V_{exp} = 7500$ km/s, $Y_e = 0.45$
Wanajo & Janka 2011, EC Supernovae in 1 and 2D
Neutron stars observed with $10^{15}$G

**Figure 2.** The $P$–$\dot{P}$ diagram shown for a sample consisting of radio pulsars, ‘radio-quiet’ pulsars and magnetars, i.e. soft-gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). Lines of constant characteristic age $\tau_c$ and magnetic field $B$ are also shown. The single hashed region shows ‘Vela-like’ pulsars with ages in the range 10–100 kyr, while the double-hashed region shows ‘Crab-like’ pulsars with ages below 10 kyr. The grey regions are areas where radio pulsars are not predicted to exist by theoretical models. The inset at the bottom-left indicates the expected direction of movement for pulsars with a braking index of $n = 1, 2$ and $3$, respectively.
3D Collapse of Fast Rotator with Strong Magnetic Fields: 15 $M_{\odot}$ progenitor (Heger Woosley 2002), shellular rotation with period of 2s at 1000km, magnetic field in z-direction of $5 \times 10^{12}$ Gauss, 

*results in* $10^{15}$ Gauss neutron star


Eichler et al. 2013
Nucleosynthesis results

- r-process peaks well reproduced
- Trough at $A=140-160$ due to FRDM and fission yield distribution
- $A = 80-100$ mainly from higher $Y_e$
- $A > 190$ mainly from low $Y_e$
- Ejected r-process material ($A > 62$):

$$M_{r, ej} \approx 6 \times 10^{-3} \, M_\odot$$
Summary

The explanation of solar system abundances up to Fe reasonably well understood, if one knows SN explosion energies

*Fe-group composition depends on $Y_e$ dialed in the explosion*

s-process is secondary, but are some features of rotation-enhanced $^{22}\text{Ne}$ visible?

*Does neutrino wind always lead to proton-rich conditions and $\nu p$-process, or also weak r-process?*

*Nucleosynthesis beyond Fe more complicated than originally envisioned (r- and p-process).*

*The classical $p/\gamma$-process cannot reproduce the light $p$-isotopes and another process has to contribute these nuclei ($\nu p$-process) and/or $p/\gamma$-process in different locations.*

*Also the r-process comes in at least two versions (weak-main/strong). Weak r-process possible in EC SNe (and Quark-Hadron EoS SNe). Any chance to become neutron-rich in the late neutrino wind?*

*The main/strong r-process site still open? Rotating core collapse events with jet ejection? Primary $^{22}\text{Ne}$ neutron source in rotating models with shear motion combined with supernova shock wave? Neutrino-induced effects in outer layers?*
Transition Supernovae to Faint Supernovae and Hypernovae

Nomoto et al. (2011)
Chemical evolution calculations Prantzos 2008 and Nomoto et al. 2006 with Weaver & Woosley, and Limongi & Chieffi yields vs. Nomoto et al. yields with and without hypernovae (50% of IMF)
Positive conspiracy among supernova yields which could lead to understanding small variations in alpha/Fe ratios in low metallicity stars (apparently originating from progenitors with different masses)?

- O and Mg (from stellar evolution) increase with stellar mass
- Si, S, Ar, Ca, Ti (and also Ni/Fe) increase with supernova explosion energies
- if explosion energies increase with progenitor mass (up to black hole formation transition), one would expect an overall increase of all alpha-elements with Fe/Ni and thus expect comparable alpha/Fe ratios for different progenitor masses.