Lecture 3: Cosmic Abundances and Their Interpretation
(in terms of astrophysical objects: stellar winds and stellar explosions)

Friedrich-Karl Thielemann
Department of Physics
University of Basel
Switzerland

Long version
How do we understand: solar system abundances...

low metallicity stars ...

galactic evolution?
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  \(^{14}\text{N}(p,\gamma)^{15}\text{O}\)

2. Helium Burning
   - \(^4\text{He} + ^4\text{He} \leftrightarrow ^8\text{Be}\)
   - \(^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}\) (n-source, alternatively \(^{13}\text{C}(\alpha,n)^{16}\text{O}\))

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

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

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

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

ongoing measurements of key fusion reactions at low energies

proton/nucleon Ratio \(Y_e\) decreases with enrichment of metals!!
Central Evolution: End Stages  
(Nomoto & Hashimoto)

Recent findings (L. Siess)  
Super AGB stars end with a ONeMg WD after igniting C-burning

\[ M < 8M_\odot \rightarrow \text{C-O White Dwarf} \]
\[ M > 8M_\odot \rightarrow \text{Fe-core} \]

mass shown is He-core mass
Central Evolution: The role of electron captures

from Nomoto & Hashimoto, increasing $E_F \propto \rho^{2/3}$ of electrons as function of density
Astrophysical Sites

Hertzsprung-Russell Diagram of Stellar Evolution from Iben, showing as end stages

- white dwarfs
- core collapse (supernovae/neutron stars, black holes, hypernovae, GRBs), pair instability SNe?

influence of reaction cross sections, e-capture in late burning stages, metallicity, rotation, magnetic fields, stellar winds on final outcome
Wind Losses During Stellar Evolution
(Effects of Rotation)

Stellar yields divided by the initial mass as a function of the initial mass for non–rotating (left) and rotating (right) models at solar metallicity (Hirschi et al. 2005, Yusof et al. 2010)
Effect of fast Rotation on Stellar Evolution and Wind Losses

Predicted evolution of $60 \, M_{\odot}$ PopIII star with 52 or 65% critical rotation (Meynet et al. 2007).

Similar results for more massive stars, which would – without rotation-enhanced mass loss – end as pair instability SNe. Evolution of $^{12}\text{C}/^{13}\text{C}$ ratio for stellar yields without or with the inclusion of fast rotators for metallicities below $Z = 10^{-5}$ solid line/dashed line (Chiappini et al. 2009), also producing primary N and increasing N/O and C/O (Hirschi et al. 2008, Yusof et al. 2010).
rotation produces primary nitrogen and later $^{22}$Ne $\Rightarrow$ enhances mass loss and s-process source
s-Process (neutron) Sources

(a) Core burning of massive stars (weak s-process)

1. Helium Burning
   \[ {^4}\text{He} + {^4}\text{He} \leftrightarrow {^8}\text{Be} \]
   \[ {^8}\text{Be}(\alpha,\gamma)^{12}\text{C}[(\alpha,\gamma)^{16}\text{O}] \]
   \[ {^{14}}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}(\alpha,n)^{25}\text{Mg} \]
   \[ T=(1-2)x10^8\text{K} \]

2. Carbon Burning
   \[ {^{12}}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne} \]
   \[ {^{12}}\text{C}(^{12}\text{C},p)^{23}\text{Na} \]
   \[ T=(6-8)x10^8\text{K} \]

Protons as well as alphas are not existing intrinsically in C-burning, as destroyed in prior H-burning and He-burning. They come from the C-fusion reaction – (a) produces only nuclei up to \( A=100-110 \) in massive stars.

(b) He-shell flashes in AGB stars (strong s-process)

Protons are mixed in from the H-shell and produce \(^{13}\text{C}\) (as in 2. above), but the latter can react with the full He-abundance in He-burning and produce a strong neutron source. (This might also be possible in fast rotating stars at low metallicities, due to shear-induced mixing).

The s-process is a secondary process, the n-captures act on heavier nuclei, formed in the previous stellar generation, in (a) also the n-source is secondary!!
in low and intermediate mass stars the H- and He-shells are located at small distances. They do not burn in a constant fashion. If the H-burning zone is on, it creates He fuel. After sufficient He is produced, He is ignited in an unburned He-rich zone (at sufficient densities and temperatures). The burning is not stable, the amount of energy created in a shallow zone is not sufficient to lift the overlaying H-shell which would cause expansion + cooling, i.e. steady burning. Instead He-burning, being dependent on the density squared, burns almost explosively (flash), causing then a stronger expansion which even stops H-burning in the H-shell. This behavior repeats in recurrent flashes. H is mixed into the unburned He fuel.
Observations of post-AGB stars, indicating the intrinsic pollution due to strong s-processing

**FIGURE 1.** Theoretical interpretation of the post-AGB star IRAS 08281-4850 by Reyniers et al. (2007a) [2], with $M_{\text{ini}}^{\text{AGB}} = 2 M_\odot$, case ST.

Gallino et al. (2008)
The s-process is a secondary process (capturing neutrons on pre-existing Fe-group nuclei). A similar neutron exposure on smaller amounts of Fe-seeds leads to stronger production of the heaviest s-nuclei (so-called lead stars).
the full process of multi-D mixing is not fully understood yet (resolution and 3D), thus the mixing efficiency is introduced by a parameter (here ST*fac)

each star shows a specific stage of s-processing, i.e. we have no overall agreement with „solar“ s-process abundances in a single star. Solar s-abundances are only obtained via integrating over an IMF and over galactic evolution with increasing metallicity
s-Processing in rotating low-metallicity stars, $Z=10^{-5}$

**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 $^{17}$O($\alpha, \gamma$) rates (B4, CF88/10) highlights the uncertainty linked to the neutron poison $^{16}$O.

Dependence on rotation and $^{16}$O neutron poison via $^{16}$O($n,\gamma$)$^{17}$O($\alpha,\gamma$) or $^{17}$O($\alpha,n$) (Frischknecht, Hirschi, Thielemann 2012) still unclear, Görres (2012) vs. Fulton (2013)
Explosions caused by accretion in binary stellar systems

Binary systems with accretion onto one compact object can lead (depending on accretion rate) to explosive events with thermonuclear runaway (under electron-degenerate conditions):
- White dwarfs (novae, type Ia supernovae)
- Neutron stars (type I X-ray bursts, superbursts?)
Novae observations: optical light curve

- \[L\] increases very fast by factors greater than \(10^4\) - absolute \(L_{\text{max}}\) \(\sim 10^{4.5}\) from M. Hernanz
Novae observations: summary of properties

- Expansion velocities of the ejecta $\sim 10^2$-$10^3$ km/s
- Ejected masses $\sim 10^{-5}$ - $10^{-4}$ $M_{\text{sun}}$
- Energetics and luminosity:
  \[ \text{K.E. } \sim 10^{45} \text{ erg} \quad \text{L} = 10^5 L_{\text{sun}} \]
- Ejecta enhanced in C, N, O (, Ne) compared to solar
- Nova rate in the Milky Way:
  $\sim 35$ per yr ( $\sim 5$ discovered optically)
Scenario

- Mass transfer from the companion star onto the white dwarf (cataclysmic variable)
- Hydrogen burning in degenerate conditions on the white dwarf surface
- Thermonuclear runaway and explosive H-burning
- Decay of short-lived radioactive nuclei in the outer envelope (transported by convection)
- Envelope expansion, L increase and mass ejection

from M. Hernanz
Thermonuclear Burning of Hydrogen: hot CNO-cycles

no breakout from the hot CNO; required enhancement of CNO (and sometimes Ne) due to mixing with WD matter in the pre-ignition simmering phase (see e.g. Casanova et al. 2010), Ne in case of ONeMg WDs (up to 1/3 of observed novae); Novae are not strong contributors to chem. evol., they contribute to specific isotopes ($^{13}$C, $^{15}$N, $^{17}$O) and possibly minor contributions to isotopes up to Mg-Si-S
X-ray burst observations

NASA RXTE: GS 1826-24 burst shape changes!
(Galloway 2003 astro/ph 0308122)

15 s

years

Flux (10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1})

Time (s)

0 5 10 15

0 5 10 15 100 150

not identical, and slow but continuous evolution in burst features, physics behind this?
Surface of an accreting neutron star

approx. $10^{-12} M_{\text{sol}}$ at ignition, with an accretion rate of $10^{17}$ g/s this corresponds to a repetition rate of about 4 hours

graph from H. Schatz

this talk

according to P. Haensel
Explosive H/He-burning and rp-process in realistic hydro models for X-ray Bursts

Fisker, Schatz, FKT (2008)
Heger, Woosley, Keek .. (2013)
Fehlmann et al. (2014)

Accretion  
\[\text{Ejection?}\]
\[\text{Radiative Zone}\]
\[\text{Convecive Burning Layer}\]
\[\text{Residual H Burning}\]
\[\text{rp process}\]
\[\text{Compression}\]

\[\text{Energy generation}\]

\[\text{Burning cycles in adjacent layers}\]

\[\text{~ 30 m}\]
\[\text{~ 20 m}\]
\[\text{~ 5 m}\]
Temperatures and Lightcurves

X-ray burst lightcurve

Duration 10-20s
from Fisker et al. (2004, 2005)

Temperature of element

first burst higher because of initial solar composition

repetition about every 20000s
Break-out Reactions and the Stability of Burning

Change in stable burst conditions due to new $^{15}$O reaction cross section (Fisker et al. 2007).
Continuous improvements in reactions (e.g. Parikh et al 2009, Cybert et al. 2010) and test of metallicity effects (e.g. Jose et al. 2012, Parikh et al. 2013)
Determines also the critical accretion rate between constant and unstable (bursts) burning

Tan et al. (2007)
Fisker, Schatz, FKT (2008)

reaction fluxes and abundances at different times during burst in ign. zone

fuel for next burst

He not fully burned

dependent on details of mass zone, H can run out shortly after seize of alpha-process
Double Peak Lightcurves due to Waiting Points

Competition between beta-decays and alpha-capture for inhibited p-captures

alternative explanation by Bhattacharyya & Strohmayer (2006): Burning spreading over neutron star surface with intermediate slow-down phase

Fisker, FKT, Wiescher (2004)
Supernova classification

Observers introduced the terms type I and II dependent on the observation of H-lines (absorption), but there seemed to be a wide variety of type I's a, b, c (discovered in early 80s)

One finds type II's and Ib/c's in regions of recent star formation and none of them in elliptical galaxies (no recent star formation) => massive stars with H/He envelope lost

In elliptical galaxies, i.e. without recent star formation, only type Ia's are found (rejuvenated binaries?)!

Filippenko 1997
Type Ia Supernovae: Accretion in Binary Stellar Systems

Binary systems with accretion onto one compact object can lead (depending on accretion rate) to explosive events with thermonuclear runaway (under electron-degenerate conditions):

- **White dwarfs** (novae, type Ia supernovae = called single degenerate)
- **Neutron stars** (type I X-ray bursts, superbursts?)
Accretion History and Outcome (old ideas): Nomoto 1982a,b, Nomoto & Kondo 1991

H-accretion

He-accretion

the accretion rate determines whether pile-up (and explosive ignition) or steady burning. Until recently ignition of He-detonations seemed to give abundance features in the outer layers inconsistent with observations.
Central Ignition
for three different accretion rates
Nomoto, Thielemann, Yokoi 1984

In spherical symmetry, such ignitions can be followed in a self-consistent manner with the aid of an implicit Lagrangian hydro-code

ignition when C-fusion energy exceeds neutrino losses
Back of the Envelope SN Ia

e.g. W7 (Nomoto, Thielemann, Yokoi 1984); delayed detonations (Khokhlov, Höflich, Müller; Woosley et al.)

\[ M_{ch} \approx 1.4M_\odot \text{ of } ^{12}\text{C}^{/16}\text{O}=1 \text{ WD} \rightarrow 1.398776 M_\odot \ ^{56}\text{Ni} \]
\[ \rightarrow 2.19 \times 10^{51} \text{ erg} \quad - \quad E_{grav} \approx (5 - 6) \times 10^{50} \text{ erg} \]

reduction due to intermediate elements like Mg, Si, S, Ca

\[ \rightarrow 1.3 \times 10^{51} \text{ erg} \quad \text{in spherically symmetric models description of the burning front propagation (with hydrodynamic instabilities) determines outcome!} \]
a deflagration (subsonic burning front) with a propagation speed related (initially) to heat conduction and (later) to mixing via Rayleigh-Taylor instabilities (treated in time-dependent mixing length theory of 0.7 times the pressure scale height).

$Y_e$ in inner zones determined by electron capture (electrons degenerate with high Fermi energy), in outer zones by metallicity ($\rightarrow^{54}\text{Fe, }^{58}\text{Ni}$).
Role of large shell model calculations for e-capture on Fe-group nuclei and role of deflagration speeds / ignition densities (high electron Fermi energies)

(a) Test for influence of new shell model electron capture rates (including pf-shell Langanke, Martinez-Pinedo 2003)
(b) Test for burning front propagation speed (Brachwitz et al. 2001, Thielemann et al. 2004) ign. densities 2,4,6,8x10^9 gcm^-3, B1,B2 deflagration speeds
direct influence on dominant Fe-group composition resulting from SNe Ia
Ignition density determines Ye and neutron-richness of (60-70% of) Fe-group

FKT et al. (2004, spher. sym. explosions with parametrized burning front)

results of explosive C, Ne, O and Si-burning:
Fe-group to alpha-elements 2/1-3/1

SNe Ia dominate Fe-group, over-abundances by more than factor 2 not permitted

maximum central density $3 \times 10^9$ g cm$^{-3}$

$^{48}\text{Ca}$, $^{50}\text{Ti}$, $^{54}\text{Cr}$ .. 
strong indicators!!
Travaglio et al. (2004), Maeda, Röpke, Fink, Hillebrandt, Travaglio, FKT (2010), 2-3D nucleosynthesis with tracer particles

Variations in central deflagrations and central as well as off-center ignited delayed detonations. Changes in $^{54}$Fe and $^{58}$Ni overproductions.
Present and future 3D models need a consistent treatment instead of parametrized spherical propagation, MPA Garching/Würzburg (Röpke et al.), U. Chicago/SUNY Stony Brook (Calder et al.)

- distribution of ignition points uncertain (deflagration, centrally ignited delayed detonation, off-center delayed detonation)
- hydrodynamic instabilities determine propagation
- deflagration/detonation transition

Explicit hydro-codes cannot handle transition to thermonuclear runaway \( \Rightarrow \) assumed ignition conditions

Changing ignition geometry/number of sparks provides handle to obtain different realizations of the DDT model

This set gives about a factor of three variation in 56Ni mass \((0.4 - 1.1 \, M_{\odot})\)
The distribution of the main abundance groups in a sample of SNe Ia. The enclosed mass of different burning products is plotted vs. Δm15 (B).

Open circles refer to stable $^{54}$Fe and $^{58}$Ni; solid circles to $^{56}$Ni, and open triangles to the sum of these. Crosses show the mass enclosed inside the layer of intermediate mass elements (IME), i.e., the total mass burned.

$^{54}$Fe and $^{58}$Ni in the SN core are roughly constant over all luminosities, while $^{56}$Ni determines the luminosity and correlates with Δm15 (B).

The mass enclosed by the position of IME’s is inferred to be similar for all SNe of the sample, and the explosion energy seems constant (from Mazzali et al. 2007).
Attempts to overcome constraints of explicit 3D hydrocodes

low Mach number hydrodynamics algorithms filter soundwaves from the system, allowing for the efficient simulation of long timescale processes (not constrained by Courant condition, permitting only timesteps of the sound crossing time between gridpoints).

Zingale (2013, Maestro code), Shown energy generation in convective region during simmering phase before SN Ia explosion. Slightly off-center ignition likely in a single point!?
Four Proposed Explosion Mechanisms

- **Central Ignition** (single or multiple Ignition points)
  - Pure Deflagration
  - Deflagration To Detonation Transition (DDT)
  - Detonation
  - Reineke et al. (1999, 2002); Schmidt et al. (2006); Jordan et al. (2009)

- **Off-Center Ignition** (single or multiple Ignition points)
  - Gravitationally Confined Detonation (GCD)
  - Plewa, Calder, Lamb (2004); Townsley et al. (2007); Jordan et al. (2008); Meakin et al. (2009)

- **Pulsationally Assisted GCD**

*Flash Center for Computational Science*
The University of Chicago
**Variations in Type Ia models**

**Double Detonations:** central detonations of Chandrasekhar mass WDs give wrong nucleosynthesis features, this is the reason why a deflagration pre-expansion is needed. Detonations of *sub-Chandrasekhar* mass WDs with lower central densities avoid this, but an ignition has to be caused artificially. This might occur during accretion instabilities of the unburned He-shell before it attains its regular (detonation) ignition mass. **If the He-layer can be minimized before He (double-)detonations the outcome could be consistent with observations** (*Bildsten et al. 2007, Kromer et al. 2010, Sim et al. 2010*)

---

**White Dwarf Collisions/Mergers:** This scenario was already discussed by Benz et al. in the 1980s, but discarded as it would only work in head-on collisions. Recent high resolution 3D calculations Rosswog+ (2010), Raskin+ (2010), Pakmor+ (2012), Garcia-Senz+ (2013) show that this could be an (although infrequent) pathway to SNe type Ia in galactic centers and globular clusters, where the statistics for such collisions is high.
Subluminous Type Ia Supernovae

from Taubenberger (2008), $\Delta m_{15} (B)_{\text{true}}$ of these SNe is given in parenthesis
Multiple Sub-Classes of SNe Ia

- Normal (70%)
- Faint and fast (91bg, 15%)
- Bright with early IGE lines (91T, 9%)
- Faint with weak IMEs (02cx, 5%)

Also a sample of very bright cases e.g. 2003fg (Howell+); 2007if (Scalzo+, Yuan+); 2009dc (Yamanaka+)... 

There are now multiple sub-classes of SNe Ia (from Li et al. 2011)

Taken from Sim (2012): what are the origins of these different Sub-classes???
Core Collapse Supernovae from Massive Stars
Neutrino-driven Core Collapse Supernovae

\[ \nu_e + n \leftrightarrow p + e^- \]
\[ \bar{\nu}_e + p \leftrightarrow n + e^+ \]
\[ \nu_e + A' \leftrightarrow A + e^- \]
\[ \nu + N \leftrightarrow \nu + N \]
\[ \nu + A \leftrightarrow \nu + A \]
\[ \nu + e^- \leftrightarrow \nu + e^- \]
\[ e^+ + e^- \leftrightarrow \nu + \bar{\nu} \]

heating

opacity

thermalization

source terms
\[ \nu = \nu_e, \nu_\mu, \nu_\tau \]
\[ e^+ + e^- \leftrightarrow \nu + \bar{\nu} \]
\[ \gamma + \gamma \leftrightarrow \nu + \bar{\nu} \]
also
\[ e + \gamma \leftrightarrow e + \gamma + \nu + \bar{\nu} \]
and
\[ \nu + \bar{\nu} \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau} \]
Supernovae in 1D

SN Simulations: $M_{\text{star}} \sim 8 \ldots 10 \, M_{\odot}$

"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)


Fischer et al. 2010

Convection is not necessary for launching explosion but occurs in NS and in neutrino-heating layer
Growing set of 2D CCSN Explosions
(here Hanke & Janka 2013 – MPA Garching)

But 3D still somewhat open!

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

There are two transitions: (i) 8-10\textsubscript{\text{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???
• 8 - 10 $M_{\odot}$ super-AGB stars when $O+Ne+Mg$ core collapses due to electron capture, produce little $\alpha$-elements and Fe-peak elements.
• 10 - 90 $M_{\odot}$ undergo Fe-core collapse. Nucleosynthesis in aspherical explosions might be important,
• 90 - 140 $M_{\odot}$ stars undergo pulsational nuclear instabilities at various nuclear burning stages, including O and Si-burning.
• 140 - 300 $M_{\odot}$ stars become pair-instability supernovae, if the mass loss is small enough.
• > 300$M_{\odot}$ Very massive stars undergo core-collapse to form intermediate mass black holes.
The GRB- Supernova Connection

Ejecta distribution in a parametrized jet-model for GRB-SNe (Maeda et al. 2002). Blue and green colors stand for Fe-group material, red for oxygen. The resulting $[\text{O I}] \lambda \lambda 6300, 6364$ profiles for different viewing angles are also shown (from Mazzali et al. 2005).
Diversity in Type Ic Supernovae

Taubenberger (2008)

Comparison of absolute magnitudes, kinetic energy, ejecta mass and Ni mass of SNe Ic.

<table>
<thead>
<tr>
<th>SN</th>
<th>$M_V$ (mag)</th>
<th>$E_{\text{kin}}/10^{51}$erg</th>
<th>$M_{\text{ej}}/M_\odot$</th>
<th>$M_{\text{Ni}}/M_\odot$</th>
<th>references</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994I</td>
<td>-17.62</td>
<td>1</td>
<td>0.9</td>
<td>0.07</td>
<td>N94,R96</td>
</tr>
<tr>
<td>2004aw</td>
<td>-18.02</td>
<td>3.5–9.0</td>
<td>3.5–8.0</td>
<td>0.25–0.35</td>
<td>this paper</td>
</tr>
<tr>
<td>2002ap</td>
<td>-17.35</td>
<td>4</td>
<td>3</td>
<td>0.08</td>
<td>M02,F03,T06</td>
</tr>
<tr>
<td>1997ef</td>
<td>-17.14</td>
<td>19</td>
<td>9.5</td>
<td>0.16</td>
<td>M00,M04</td>
</tr>
<tr>
<td>1998bw</td>
<td>-19.13</td>
<td>30</td>
<td>10</td>
<td>0.70</td>
<td>G98,N00</td>
</tr>
</tbody>
</table>

For all SNe except SN 2004aw, the values for kinetic energy, ejecta mass, and nickel mass have been inferred from light curve and spectral models.

N94 = Nomoto et al. 1994;
R96 = Richmond et al. 1996;
M02 = Mazzali et al. 2002;
F03 = Foley et al. 2003;
T06 = Tomita et al. 2006;
M00 = Mazzali, Iwamoto & Nomoto 2000;
M04 = Mazzali et al. 2004;
G98 = Galama et al. 1998;
N00 = Nakamura et al. 2000
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 1.2B at $S=4k_B/b$, Nomoto/Umeda/Thielemann applied thermal bomb and integrate from outside until expected $^{56}$Ni-yield.
Radioactivity Diagnostics of SN1987A: $^{56}\text{Ni}/\text{Co}$, $^{57}\text{Ni}/\text{Co}$, $^{44}\text{Ti}$

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

total/photon decay energy input from models
Nucleosynthesis problems in “induced” piston or thermal bomb models utilized up to present to obtain explosive nucleosynthesis yields with induced explosion energies of $10^{51}$ ergs. 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 -> $Y_e$
(ii) multi-D

$Y_e$ determines Fe-group isotopes.
Arnould (1976) and Woosley & Howard (1978) suggested, opposite to initial ideas of B²FH, photodisintegrations of pre-existing heavy (s-process) nuclei, which occur in the thermal bath of supernova explosions in explosive Ne/O-burning layers with peak temperatures of 2-3 $10^9$ K.

Arnould & Goriely (2003)
Comparison with solar p-only nuclei

Goriely & Arnould (2003)

Rapp et al. (2007)

Dillmann et al. (2008)

variation of rate uncertainties
Wooley & Heger (2007): Results for initial solar metallicity, integrated over a Salpeter initial mass function and divided by initial abundances -> overproduction factors. Intermediate mass elements well reproduced, Fe/Ni-group depends on choice of mass cut/location of piston, well pronounced weak s-process, absence of r-process as not included in modeling, p-process isotopes only well reproduced at high end.
Cayrel et al. (2004). taken as representative sample for low metallicity stars (representing type II supernova yields). E: “Standard” IMF integration of yields from $M = 10^{-100} \, M_\odot$, explosion energy $E = 1.2 \, B$ (underproduction of Sc, Ti, Co and Zn).
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)
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 $\rightarrow$ high $E_F$ for electrons $\rightarrow$ e-captures dominate $\rightarrow$ n-rich composition

- if el.-degeneracy lifted for high $T$ $\rightarrow$ $\nu_e$-capture dominates $\rightarrow$ due to n-p mass difference, p-rich composition

- in late phases when proto-neutron star neutron-rich, $\nu_e$'s see smaller opacity $\rightarrow$ higher luminosity, dominate in neutrino wind $\rightarrow$ 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 $E_{\nu,\bar{\nu}} - E_{\bar{\nu},\nu} > 4(m_n - m_p)$ 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 $^{64}\text{Ge}$, due to (low) densities and a long beta-decay half-life (decaying to $^{64}\text{Zn}$).

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.

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.

Anti-neutrino capture on protons provides always a small background of neutrons which can mimic beta-decay via (n,p)-reactions.
vp-process studies (Wanajo, Janka, Kubono 2010), including different neutron star masses and reverse shock effects/positions
Observational Constraints on r-Process Sites

Apparently uniform abundances above Z=56 (and up to Z=82?) -> “unique” astrophysical event for these “Sneden-type” stars

Weak (non-solar) r-process in Honda-type stars related to massive stars due to “early” appearance at low metallicities (behaves similar to SN II products like O, but with much larger scatter), why the large scatter?

Cowan and Sneden

Observations of a/the? weak r-process?
Working of the r-Process

**Explosive Si-Burning**

1. **(very) high entropy alpha-rich** (charged-particle) freeze-out with upper equilibrium group extending up to $A=80$
   - *quasi-equilibria in isotopic chains* *(chemical equilibrium for neutron captures and photodisintegrations)* with maxima at specific neutron separation energies $S_n$
   - neutron/seed($A=80$) ratio and $S_n$ of r-process path dependent on entropy and $Y_e$

   (many parameter studies: Meyer, Howard, Takahashi, Janka, Hoffman, Qian, Woosley, Freiburghaus, Thielemann, Mathews, Kajino, Wanajo, Otsuki, Terasawa, Mocelj, Farouqi, Kratz, Goriely, Martinez-Pinedo, Arcones, Panov, Petermann ...)

2. **low entropies and normal freeze-out** with very low $Y_e$,
   - from expanding neutron star-like matter leading also to large $n$/seed ratios
   - $S_n$ function of $Y_e$

   (Freiburghaus, Rosswog, Thielemann, Panov, Goriely, Janka)
What is the site of the r-process?

from S. Rosswog

NS mergers, BH-NS mergers, problems: ejection too late in galactic evolution (or alternatively polar jets from supernovae, Cameron 2003)

from H.-T. Janka

SN neutrino wind, problems: high enough entropies attained? neutrino properties???
What is the site of the r-process(es)?

- **Neutrino-driven Winds (in supernovae?)?** *Arcones, Burrows, Janka, Farouqi, Hoffman, Kajino, Kratz, Martinez-Pinedo, Mathews, Meyer, Qian, Takahara, Takahashi, FKT, Thompson, Wanajo, Woosley ... (no!?)*

- **Electron Capture Supernovae?** *Wanajo and Janka (weak!)*

- **SNe due to quark-hadron phase transition** *Fischer, Nishimura, FKT (if? weak!)*

- **Neutron Star Mergers?** *Freiburghaus, Goriely, Janka, Bauswein, Panov, Arcones, Martinez-Pinedo, Rosswog, FKT, Argast, Korobkin*

- **Black Hole Accretion Disks (massive stars as well as neutron star mergers, neutrino properties)** *MacLaughlin, Surman, Wanajo, Janka, Ruffert*

- **Explosive He-burning in outer shells (???)** *Cameron, Cowan, Truran, Hillebrandt, FKT, Wheeler, Nadyozhin, Panov*

- **CC Neutrino Interactions in the Outer Zones of Supernovae** *Haxton, Qian (abundance pattern?)*

- **Polar Jets from Rotating Core Collapse?** *Cameron, Fujimoto, Käppeli, Liebendörfer, Nishimura, Nishimura, Takiwaki, FKT, Winteler*
What determines the neutron/proton or proton/nucleon=Ye ratio?

\(Y_e\) 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 \(\rightarrow\) high \(E_F\) for electrons
  \(\rightarrow\) \(e\)-captures dominate \(\rightarrow\) n-rich composition

- if el.-degeneracy lifted for high \(T\) \(\rightarrow\) \(\nu_e\)-capture
  dominates \(\rightarrow\) due to n-p mass difference, p-rich
  composition

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 \(E_{\bar{\nu}_e,\bar{\nu}} - E_{\nu_e,\nu} > 4(m_n - m_p)\) lead to \(Y_e < 0.5\)!

General strategy for a successful r-process:
1. either highly neutron-rich initial conditions + fast expansion (avoiding neutrino interactions!)
2. have neutrino properties to ensure (at least slightly) neutron-rich conditions (+ high entropies)
3. invoke (sterile?/collective) neutrino oscillations
Individual Entropy Components

Farouqi et al. (2010), above $S=270-280$ fission back-cycling sets in HEW, ETFSI-Q, $V_{\text{exp}}=7500$ km/s, $Y_e=0.45$
Superposition of entropies for different mass models

Farouqi et al. (2010)

This is a set of superpositions of entropies with a given expansion speed (or timescale) and $Y_e$. A superposition of expansion velocities might be needed as well, if running into preexpanded material, shocks etc. (Arcones et al. 2007, Panov & Janka 2009, Wanajo 2008). That relates also to the question whether we have a “hot” or “cold” r-process, if chemical equilibria are attained and how long they persist.
Possible Variations in Explosions and Ejecta

- regular explosions with neutron star formation, neutrino exposure, \( \nu_p \)-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)
- under which (special?) conditions can very high entropies be obtained which produce the main r-process nuclei?

Izutani et al. (2009)

- \( \gamma_e \) uncertain
- \( \gamma_e \) after explosion
- requires average anti-neutrino energies to be 5.2 MeV larger than neutrino energies (not seen in long-term simulations of Janka & Hüdepohl, Fischer et al. 2010)
Long-term evolution up to 20s, transition from explosion to neutrino wind phase

Fischer et al. (2010) these 2010 findings see a longterm proton-rich composition, late(r) transition to neutron-rich ejecta possible?

\( Y_e > 0.5 \)
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 \(Ye=0.4\) (but probably not sufficient Entropies to cause strong r-process)!

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 \(Y_e = 0.035\).
Observational indications: heavy r-process and Fe-group uncorrelated, Ge member of Fe group, Zr intermediate behavior, weak correlations with Fe-group as well the heavy r-elements (Cowan et al. 2005)
The SN II and Ia rates compared with the NS merger rate (100 yr\(^{-1}\)).
The present time NS merger rate reproduces the observed present time NS merger rate of 83/Myr (Kalogera et al. 2004).
This is obtained with alpha=0.018 (fraction of NS mergers from total NS production rate).

**The rate of mergers is by a factor of about 100 smaller than CCSNe,**
**but they also produce more by a factor of 100 than required if CCSNe would be the origin**
Neutron Star Mergers are observed
A ‘kilonova’ associated with the short-duration γ-ray burst GRB 130603B

Short-duration γ-ray bursts (less than about two seconds) are produced by a relativistic jet created by the merger of two compact stellar objects (specifically two neutron stars or a neutron star and a black hole). Mergers of this kind are also expected to create significant quantities of neutron-rich radioactive species, whose decay should result in a faint transient, known as a ‘kilonova’, in the days following the burst. Recent calculations suggest that much of the kilonova energy should appear in the near-infrared, because of the high optical opacity created by these heavy r-process elements. Here we report optical and near-infrared observations of such an event accompanying the short-duration γ-ray burst GRB 130603B.
Fission Cycling in Neutron Star Mergers

Trajectory from Freiburghaus, Rosswog, and Thielemann 1999
($Y_e = 0.1, n/Seed = 238$).

Panov, Korneev and Thielemann (2007, 2009) with parametrized fission yield contribution (see also Goriely, Bauswein, Janka 2011)

Martinez-Pinedo et al. (2006)
Recent neutron star merger updates (Korobkin et al. 2012)

Variation in neutron star masses fission yield prescription
Eichler et al. (2014)
Variations in fission yield distributions (ABLA from Kelic et al. GSI).
Fills somewhat $A=140-1$ gap and moves $A=195$ peak down slightly (related to fission yield distribution and corresponding neutron emission).

The final abundance pattern also depends when the neutron capture from fission neutrons occurs. If still $n,\gamma,\gamma,n$ equilibrium persists, the fit is better than with late neutron capture in a type of $n$-process. The first is the case if beta-decay rates above $Z=80$ are faster (recent evidence).
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.

Neutron stars observed with $10^{15} G$
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 Ye
- A > 190 mainly from low Ye
- Ejected r-process material (A > 62):
  \[ M_{r, ej} \approx 6 \times 10^{-3} \, M_\odot \]
Argast et al. (2004): Do neutron star mergers show up too late in galactic evolution?

**Fig. 4.** Evolution of [Eu/Fe] and [Ba/Fe] abundances as a function of metallicity [Fe/H]. NSM with a rate of $2 \times 10^{-4}$ yr$^{-1}$, a coalescence mescale of $10^6$ yr and $10^{-3}$ $M_\odot$ of ejected r-process matter are assumed to be the dominating r-process sources. Symbols are as in Fig. 1. The

Although they can be the dominant contributors in late phases?
Heavy Element Summary

The explanation of solar system abundances above Fe is much more complicated than originally envisioned (r- and p-process).

1. 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..

2. Also the $r$-process comes in at least two versions (weak-main/strong). The weak $r$-process is probably related to regular core collapse supernovae and might emerge from the late neutrino wind. The main/strong $r$-process comes apparently in each event in solar proportions, but the events are rare. The site is not found, yet. Speculations include rotating core collapse events with jet ejection, neutron star mergers and even accretion disks around black holes.