EXPLOSIVE NUCLEOSYNTHESIS
IN
CORE-COLLAPSE-SUPERNOVAE

Else PLLUMBI
(MPA-IMPRS-PhD)

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OUTLINE

INTRODUCTION

CORE-COLLAPSE-SUPERNova NUCLEOSYNTHESIS

EXPLOSIVE NUCLEOSYNTHESIS
  Si burning
  O burning
  Ne & C burning

νp-PROCESS

r-PROCESS

CONCLUSIONS
WHERE DO THE ELEMENTS (OR WE!) COME FROM?

“ONION-SKIN” STRUCTURE IN MASSIVE STARS (M>8 Msol)

Magic numbers:
N or Z=2,8,20,28,50,82,126
SUPERNOVAE EXPLOSIONS

CRAB NEBULA

CASSIOPEIA A
CORE-COLLAPSE AND SUPERNOVAE EXPLOSIONS

\[ M_{\text{cor}} = M_{\text{Ch}} \simeq 1.4 M_{\text{sol}} \]

- gravitational instability
- e-capture into nuclei
- photodisintegration of Fe-peak nuclei

\[ \rho_{\text{cor}} \simeq \rho_{\text{sat}} \simeq 10^{14} \text{ g/cm}^3 \]

- Inner-core bounces
- shock wave

\( \nu \)-driven wind = flow of neutrons and protons from the region near to the surface of the Proto Neutron Star (PNS) driven by the strong \( \nu_e \) and \( \bar{\nu}_e \) fluxes.
EXPLOSIVE NUCLEOSYNTHESIS

creation of elements by the explosion itself, that is by the high T associated with the passage of the shock

\[ aT_p \frac{4\pi r_0^3}{3} = E \]

explosion energy

peak-temperature due to the shock

necessary condition for explosive modification of the pre-explosive composition is:

\[ \tau_{\text{nucl}} \ll \tau_{\text{HD}} \]

typical time for the density to e-fold

burning life-time at \( T_p \)

\[ \tau_{\text{nucl}} = \frac{q_{\text{nucl}}}{S_{\text{nucl}}} \]

nuclear energy generation rate

nuclear energy

\[ \tau_{\text{HD}} \approx \frac{446}{\rho^{1/2}} s \]
EXPLOSIVE SILICON BURNING

\[ T > 5 \, \text{GK}, \quad \rho \sim 10^8 \, \text{g/cm}^3 \quad \rightarrow \quad \text{complete Si burning in NSE} \]

The abundance of any nucleide in NSE is determined by:

- temperature,
- density and neutron excess \( \eta \)

\[ \eta \equiv \sum (N_i - Z_i) \frac{X_i}{M_i} = 1 - 2Y_e \]

\[ e.g. \quad M = 25M_{sol}, \quad \eta \approx 0.003 \quad \rightarrow \quad ^{56}Ni \quad \text{main product among the Fe peak elements} \]

N.B: exactly the same products would be obtained if, at the same \( T \), the burning nuclear fuel is not \(^{28}Si\) but instead any other species with \( \eta = 0.003 \)

expansion \( \rightarrow \) \( T \) decreases \( \rightarrow \) nuclear reactions fall out of equilibrium at a certain \( T \) freeze-out:

1) if \( \rho \) and \( \tau_{HD} \) are “sufficiently large” \( \rightarrow \) few \( p, n, \alpha \) and composition made mainly of Fe peak nuclei

2) if \( \rho \) and \( \tau_{HD} \) are “sufficiently small” \( \rightarrow \alpha \) rich freeze-out

observed \( \gamma \) ray emitter \( \leftarrow \quad ^{44}Ti, \tau_{1/2} \approx 60 \text{yr}!! \)

N.B \( T = (4-5) \text{GK} \quad \rightarrow \quad ^{28}Si \quad \text{burns in quasi-NSE (QSE)} \)

expansion causes freeze-out where a lot of \(^{28}Si\) remains incomplete Si burning
EXPLOSIVE OXYGEN BURNING

$T = (3-4) \text{ GK}$

The fuel $^{16}O$ is dissociated giving rise to two QSE clusters in the mass region of $\text{Si}$ and $\text{Fe-peak}$ nuclei.

$T \text{ "low"}$

More material remains locked in the Si region than is converted to the Fe-peak elements.

Driving reactions:

$^{16}O(^{16}O, \alpha)^{28}\text{Si}$

$^{16}O(^{16}O, p)^{31}\text{P}$

$^{16}O(^{16}O, n)^{31}\text{S}$

$^{16}O(^{16}O, d)^{30}\text{P}$

Higher $T$ and lower $\rho$ favors:

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

After freeze-out the most abundant elements are:

${^{28}\text{Si}}, {^{32}\text{S}}, {^{36}\text{Ar}}, {^{40}\text{Ca}}$
EXPLOSIVE NEON & CARBON BURNING

$T = (2-3) \text{ GK}$

- $T$ and $\rho$ too small for QSE
- Nuclear reactions operate far from equilibrium
- The abundance of the produced elements depends on: $T$, $\rho$, $\eta$, $Y_0$ and thermonuclear reaction rates

Ne burning creates similar products to C burning

Main reactions:

$$^{20}\text{Ne} (\gamma, \alpha)^{16}\text{O} \rightarrow (\alpha, n) \quad \text{and} \quad (\alpha, p)$$

$p$ and $n$ are captured leading to the production of many rare (or neutron rich) isotopes with $A = (36-38)$

$$^{12}\text{C} + ^{12}\text{C} \quad \rightarrow \quad n^{23}\text{Mg} \quad \alpha^{20}\text{Ne} \quad \quad p^{23}\text{Na}$$

N.B. the outer layers of the star are heated at $T_p < 2\text{ GK}$

No explosive nucleosynthesis for them!
Early $\nu$-wind is proton-rich ($Y_e>0.5$) and is ejected at $T>10$ GK

$\nu p$ nucleosynthesis in “4 steps“:

1) Expansion and cooling ($T=(10-5)$ GK):
   $n+p$ give $\alpha$ (and residual p)

2) $T=(5-3)$ GK:
   $\alpha$ combine to heavier nuclei with $N=Z$ e.g. $^{64}Ge$

3) $T=(3-1)$ GK:
   \[ p + \nu_e \rightarrow n + e^+ \]
   important for fast $(n,p)$ reactions:
   \[ n + ^{64}Ge \rightarrow ^{64}Ga + p \]
   \[ ^{64}Ga + p \rightarrow ^{65}Ge + \gamma \]  
   N.B.

4) $T=1.5$ GK:
   $(p,\gamma)$ freeze-out and $(n,p)$ reactions and $\beta$ decays convert the heavy nuclei to stable n-deficient daughters giving rise to the $\nu p$-process
the $\nu p$-process accounts for the solar abundance of some elements e.g. Mo, Ru which are significantly underproduced in other scenarios.

...but the $\nu p$-process is sensitive to:
1) details of explosion mechanism;
2) the mass of the PNS;
3) $Y_e$;
4) $\nu$ luminosity and energy;
5) nuclear physics uncertainties:
   a) slow $3\alpha$ reaction rate (bottleneck for the seed nuclei);
   b) $(n,p)$ reaction rates on the waiting point nuclei;

based on the theory of Hauser-Feshbach

sensitivity of the element production to the nuclear reaction rates
NUCLEOSYNTHESIS OF THE ELEMENTS BEYOND Fe: THE r-PROCESS

neutron capture nucleosynthesis:

- s(low)-process: $N_n = 10^7 - 10^{10} \text{ cm}^{-3} \left( \tau_{n-capt} \gg \tau_{\beta-decay} \right)$
- r(apid)-process: $N_n = 10^{20} - 10^{30} \text{ cm}^{-3} \left( \tau_{n-capt} \ll \tau_{\beta-decay} \right)$

production of the n-rich nuclei in very n-rich environment

neutrons accumulate to the magic N and when the intense neutron flux terminates the nuclei $\beta$ decay

nuclei approach the valley of stability from the neutron rich side
NUCLEOSYNTHESIS OF THE ELEMENTS BEYOND Fe: THE r-PROCESS

r-process is sensitive to:

1) nuclear masses ;
2) $\beta$-decay half-lives;
3) n-capture reaction rates; but experimental data do not exist for very n-rich or exotic nuclei...

r-process sites? SNe ?

r-process abundances for different nuclear mass models unlikely...

recent long-term simulations
proton-rich neutrino driven wind

Neutron star mergers ?

they are attractive r-process sites...but the time-scale for the mergers to develop is inconsistent with the data
CONCLUSIONS

We gave an overview of the core-collapse-Supernovae (ccSNe) explosions;

We saw how elements can be produced thanks to the propagation of the shock-wave to the different layers of the star (explosive nucleosynthesis)

We discussed the $^\nu$p-process and the r-process which account for the production of the p-rich and the n-rich nuclei respectively

a lot of questions still are open, such as the site of the r-process, and a lot of uncertainties concerning the element abundance constrains are due to the lack of nuclear experimental data

A lot of work has still to be done from both the astrophysical, and nuclear physics point of view to better understand from where do we come!
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THANK YOU VERY MUCH FOR YOUR ATTENTION!