Explosive nucleosynthesis
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Themes

- Scenarios of explosive nucleosynthesis
  - Accreting white dwarfs: classical novae, thermonuclear supernovae
  - Massive stars: core collapse supernovae
  - Accreting neutron stars: x-ray bursts
  - (Mergings of neutron stars..)
- Synthesis of nuclides up to Fe: supernovae of all types, novae
- Synthesis of heavier nuclei: r (and s), p and rp processes
- Observational clues:
  - Chemical evolution of the Galaxy
  - Individual stars
  - Galactic radioactivity
  - Primitive meteorites
Solar System abundances (by mass number)

- α-nuclei
- Fe-peak

Graph showing the abundances of various elements in the Solar System, with peaks for elements like Fe and valleys for α-nuclei.
Sites of explosive nucleosynthesis

- **SUPERNOVAE:**
  - Thermonuclear supernovae (SN Ia): exploding white dwarfs in binary systems (no remnant)
  - Core collapse supernovae (SN II, SN Ib/c): exploding massive stars \((M \geq 10 \, M_\odot)\) (neutron star or black hole remnant)
    \[ v \sim 10^4 \, \text{km/s}, \quad E \sim 10^{51} \, \text{erg}, \quad M_{ej} \sim M_\odot \]

- **CLASSICAL NOVAE:**
  - Explosion of the external H-rich accreted shells of a white dwarf in a binary system
    \[ v \sim 10^2 - 10^3 \, \text{km/s}, \quad E \sim 10^{45} \, \text{erg}, \quad M_{ej} \sim 10^{-4} - 10^{-5} \, M_\odot \]
White dwarfs in close binary systems

**Effect of accretion:** depends on L and M of the WD, accretion rate and chemical comp. of accreted matter \( \rightarrow \) properties of the binary system: \( M_1, M_2, P_{\text{orb}} \rightarrow A, (dM/dt)_{\text{accr}} \)

- explosive H-nuclear burning \( \rightarrow \) on top of the WD \( \rightarrow \)
  - envelope ejection, Nova explosion: \( E \sim 10^{45} \text{ erg}, M_{\text{ejected}} \sim 10^{-4-5} M_\odot, v_{\text{eject}} \sim 10^{2-3} \text{ km/s}, (H, He, CNO, Ne, ...), \sim 30/\text{yr} \) in the Galaxy

- “central” explosive C burning \( \rightarrow \) total disruption of the star, thermonuclear Supernova (Ia): \( E \sim 10^{51} \text{ erg}, M_{\text{ejected}} \sim M_{\text{WD}} (10^{33} M_\odot), v_{\text{eject}} \sim 10^4 \text{ km/s} \) (Fe, Si, Ca...), \sim 1/100 yr in the Galaxy

(Can novae accumulate enough mass to finally explode as SNIa?)
Other sites of explosive nucleosynthesis

• X-ray bursts:
  * Thermonuclear flashes on accreting neutron stars: unstable burning of H and He. Very short rise times and durations (∼10 s); recurrence times ∼ hrs - days

\[ E \sim 10^{39} \text{ erg}, \quad M_{ej} \sim 0 \]

  * Superbursts: X-ray bursts lasting 1000 times longer and releasing 1000 times more energy (10^{42} \text{ erg}); recurrence times uncertain (up to ∼5 years). Probably related to C burning

  * Some ultracompact LMXBs with high Ne/O ratios (observed in X-rays with ASCA, Chandra...) exhibit X-ray bursts, in apparent contradiction with H and He depletion in donor stars (Juett et al. 2003): spallation of accreted elements (Bildsten et al. 1992)?
Thermonuclear supernovae
Explosive nucleosynthesis in thermonuclear supernovae

- Defining characteristic of SN Ia: lack of H and presence of Si II ($\lambda_{6355}$) in spectrum

- Other observational properties:
  - homogeneity: $\sim 90\%$ of all SN Ia have similar spectra, light curves and peak absolute magnitudes
  - SN Ia appear in both elliptical and spiral galaxies

  thermonuclear disruption of mass accreting CO white dwarfs

- Scenario?
Scenario of thermonuclear supernovae

What’s the binary system progenitor of type Ia supernovae?

• Single degenerate scenario
  WD + Normal companion
  (H or He accretion)
• Double degenerate scenario
  WD + WD merging
  (He or C-O accretion)
Explosive nucleosynthesis in thermonuclear supernovae

- Defining characteristic of SN Ia: lack of H and presence of Si II ($\lambda6355$) in spectrum

- Other observational properties:
  • homogeneity: $\sim$ 90% of all SN Ia have similar spectra, light curves and peak absolute magnitudes
  • SN Ia appear in both elliptical and spiral galaxies

  thermonuclear disruption of mass accreting CO white dwarfs

- Scenario?

  - Mass of the white dwarf: Chandrasekhar or sub-Chandrasekhar?
    ➢ relation with the explosion mechanism
Thermonuclear supernovae: explosion mechanisms

Central carbon ignition: Chandrasekhar mass model

Detonation: supersonic flame
If $\rho > 10^7$ g/cm$^3$ $\Rightarrow$ C,O $\rightarrow$ Ni
If $\rho \leq 10^7$ g/cm$^3$ $\Rightarrow$ C,O $\rightarrow$ Si,Ca, S, ...

Deflagration: subsonic velocity
laminar flame: $v \sim 0.01$ c$_s$

The laminar flame becomes turbulent (Rayleigh-Taylor instability)

Deflagration + detonation: delayed detonation

Flame surface increases effective velocity increases
Turbulent flame: $v \sim 0.1 - 0.3$ c$_s$
Thermonuclear supernovae: explosion mechanisms

- Off-center ignition: sub Chandrasekhar mass model
  - $M_{\text{He}} \sim 0.2 - 0.3 \, M_{\odot}$
  - $M_{\text{CO}} \sim 0.5 - 1.1 \, M_{\odot}$
  - He-detonation
  - C-detonation
  - Pressure wave
Explosive nucleosynthesis in thermonuclear supernovae

Nucleosynthesis in multi-dimensional SNIa explosions
Travaglio et al. 2004, A&A

coupling of a tracer particle method to 2D and 3D Eulerian hydrodynamic SNIa calculations

**Fig. 4.** Radial distribution of the tracer particles in the 3D model at the beginning of the simulation.
Explosive nucleosynthesis in thermonuclear supernovae

Travaglio et al. 2004

Chandrasekhar mass model pure deflagration model in 3D

Main differences w.r.t. W7:
- $^{56}\text{Fe}$ smaller
- unburnt $^{12}\text{C}, ^{16}\text{O}, ^{22}\text{Ne}$

Fig. 9. Nucleosynthetic yields (in mass fraction normalized to the solar value and to the corresponding solar ratio) obtained using 19683 tracer particles in the 3D model $b30.3d.768$ compared to the W7 yields given by Thielemann et al. (2003).
Important diagnostic of explosion mechanism: observation of gamma-rays

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- \( \text{e}^- \) capture
- \( \beta^+ \)
- \( \beta^- \)

Radioactive isotopes relevant for \( \gamma \)-ray line astronomy
SNe Ia: $\gamma$-ray spectral evolution

Deflagration Delayed detonation

Detonation Sub-Chandrasekhar

- DEF only shows the continuum
- DEL, DET, SUB display strong lines
- $^{56}$Ni still present
- $^{56}$Ni & $^{56}$Co prominent in SUB/DET

Presence of low Z elements: continuum extends to lower energies in DEF & DEL

Gómez-Gomar, Isern, Jean (1998)
SNe Ia: $\gamma$-ray spectral evolution

Deflagration Delayed detonation
Detonation Sub-Chandrasekhar

- $^{56}$Ni lines have disappeared
- 122 - 136 keV $^{57}$Co lines appear
- the energy cut-off of DEF is still low

Gómez-Gomar, Isern, Jean (1998)
Gamma-rays provide diagnostics of the explosion mechanism

\[
\frac{F(847)_{200\text{d}}}{F(158)_{\max}} \propto \frac{(^{56}\text{Ni})_{\text{tot}}}{(^{56}\text{Ni})_{\text{surface}}}
\]

\[
F(847)_{200\text{d}}/F(158)_{\max}
\]

DEF 8
DEL 2.2
SUB 1.3
DET 0.7

Gómez-Gomar, Isern, Jean (1998)
**WARNING:** lines are very broad: detectability very difficult

- 5 Mpc (DEFa, $\Delta E=20$ keV, 100 days)
- 8 Mpc (DET, $\Delta E=40$ keV, 70d)

*INTEGRAL/SPI* (847 keV line):

*Isern, Bravo, Hirschmann, García-Senz, 2004*
Core collapse supernovae
Synthesis of radioactive isotopes in core collapse supernovae

Models
* Thielemann, Nomoto and Hashimoto (1996): $M = 13 - 25 \, M_\odot$, $Z_\odot$
  (Nakamura et al. 1999: effect of low $Z$)
  - Explosion induced by depositing thermal $E$ in the Fe core “thermal bomb”
* Woosley and Weaver (1995): $M = 11 - 40 \, M_\odot$, $Z = 0, 10^{-4} - Z_\odot$
  - Explosion induced by piston located at the outer edge of the Fe core
* Limongi and Chieffi (2003), Rauscher et al. (2002) ...

Some results: “3 coarse classes of nuclei” (Rauscher 2004)
• determined by stellar evolution only (mainly hydrostatic); $Y = f(M)$
  ➢ sensitive to uncertainties in the reaction rates and to mixing ...
  He, C, O, Ne, Mg, $^{26}$Al, $^{60}$Fe (very dependent on $^{59}$Fe(n,γ)$^{60}$Fe)
• depend on stellar evolution and explosion energy; weakly dependent on $M$
  Si, S, Ar, Ca
• probe the explosion mechanism: depend on size of pre-SN Fe core, $M_{\text{cut}}$, $E_{\text{explosion}}$, electron abundance $Y_e$ (neutronization)
$^{44}$Ti, Fe group ($^{56,57}$Ni), $r$-process elements
$^{56,57}\text{Ni}$ and $^{44}\text{Ti}$ production in core collapse supernovae

$^{56,57}\text{Ni}$: explosive Si burning

$^{44}\text{Ti}$: produced during $\alpha$-rich freezout from NSE in the hottest and deepest layers ejected during the explosion (also in sub-Ch SNIa)

- large sensitivity to mass cut location and amount of mass fallback

- $M(44\text{Ti}) < 10^{-4} M_\odot$ (\(M \geq 30 M_\odot\) $\Rightarrow$ no $^{44}\text{Ti}$ ejection)

- $^{44}\text{Ti}$ ejection accompanied by $^{56,57}\text{Ni}$

Diagnostic of models: observation of individual objects

- $\gamma$-ray lines: $^{56,57}\text{Ni}$ and $^{44}\text{Ti}$ yields (better in SN Ia; detected in SN 1987A)

- bolometric light curves
$^{56,57}\text{Ni}$ and $^{44}\text{Ti}$

production sites

Explosive burning in massive stars (core collapse supernovae)

$^{56,57}\text{Ni}$ and $^{44}\text{Ti}$ are produced in the same internal zones

Diehl & Timmes, 1998
\textbf{56,57}Ni and \textbf{44}Ti production in core collapse supernovae

\textbf{56,57}Ni: explosive Si burning

\textbf{44}Ti: produced during $\alpha$-rich freezout from NSE in the hottest and deepest layers ejected during the explosion

$\longrightarrow$ large sensitivity to mass cut location and amount of mass fallback

$\longrightarrow$ $M(\text{44} \text{Ti}) < 10^{-4} \, \text{M}_\odot$ \hspace{1cm} ($M \geq 30 \, \text{M}_\odot \Rightarrow \text{no 44} \text{Ti ejection}$)

$\longrightarrow$ \text{44}Ti ejection accompanied by \textbf{56,57}Ni

Diagnostic of models: observation of individual objects

- $\gamma$-ray lines: \textbf{56,57}Ni (better in SN Ia; but detected in SN 1987A), and \textbf{44}Ti yields
- bolometric light curves: idem ($\tau$: 111d, 390d, 89 yrs)
\textit{Fig. 1: The bolometric light curve of SN1987A, and its relation to energy input from radioactivities of different decay time scales (from Diehl & Timmes 1998)}
Consequences of nuclear electron captures in core collapse supernovae

Realistic treatment of e-capture on heavy nuclei (A>60) implies significant changes in the hydrodynamics of core collapse and bounce, and also on postbounce evolution.

†see for instance Hix et al. 2003, Phys. Rev Let. (ask Martinez Pinedo)

†Still fail to produce an explosion in the spherically symmetric case, but mass behind the shock when it is launched is reduced by 20%, neutrino L is boosted by 15% ...
Classical Novae
Scenario of classical novae

Mass transfer from the companion star onto the white dwarf (cataclysmic variable) →
Hydrogen burning in degenerate conditions on top of the white dwarf →
Thermonuclear runaway →
Explosive H-burning

Decay of short-lived radioactive nuclei in the outer envelope (transported by convection) →
Envelope expansion, L increase and mass ejection
**Nova Models: Thermonuclear Burning of Hydrogen. CNO cycle**

- **Start:** $\tau_{\beta^+} < \tau(p,\gamma)$
  - CNO cycle operates in equ.
- **T $\sim 10^8$ K:** $\tau_{\beta^+} > \tau(p,\gamma)$
  - CNO cycle $\beta^+$-limited (bottle neck)
- **Convection:**
  - Fresh fuel brought to the burning shell
  - $\tau_{\text{conv}} < \tau_{\beta^+}$: $\beta^+$-unstable nuclei to external cooler regions where they are preserved from destruction

Later decay on the surface leads to expansion and luminosity increase.
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<td>12.</td>
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<tr>
<td>V977 Sco</td>
<td>1990</td>
<td></td>
<td>0.51</td>
<td>0.38</td>
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<td>0.026</td>
<td>0.0077</td>
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<td>V433 Sct</td>
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<td>V351 Pup</td>
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<td>V1974 Cyg</td>
<td>1992</td>
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<td>0.0051</td>
<td>0.49</td>
<td>27.</td>
<td>68.</td>
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</tr>
<tr>
<td>V1974 Cyg</td>
<td>1992</td>
<td></td>
<td>0.30</td>
<td>0.52</td>
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<td>0.023</td>
<td>0.10</td>
<td>0.037</td>
<td>0.075</td>
<td>0.18</td>
<td>9.7</td>
<td>21.</td>
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<td>V838 Her</td>
<td>1991</td>
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<td>0.60</td>
<td>0.31</td>
<td>0.040</td>
<td>0.030</td>
<td>0.028</td>
<td>0.015</td>
<td>0.40</td>
<td>21.</td>
<td>9.7</td>
<td>12.</td>
</tr>
</tbody>
</table>

- **V1370 Aql 1982**: Z = 0.86 = 45 Z☉; Ne = 0.56 = 296 Ne☉
- **QU Vul 1984**: Z = 0.44 = 23 Z☉; Ne = 0.18 = 100 Ne☉
Nova Models: need of core-envelope mixing

- $Z$ observed $>>$ solar $\rightarrow$ mixing CO or ONe core – solar envelope accreted
- Explosion itself (fast nova) $\rightarrow$ initial overabundance of CNO $\rightarrow$ mixing
Many classical nova ejecta are enriched in CNO and Ne. Rosner and coworkers recently suggested that the enrichment might originate in the resonant interaction between large-scale shear flows in the accreted H/He envelope and gravity waves at the interface between the envelope and the underlying C/O white dwarf. The shear flow amplifies the waves, which eventually form cusps and break. This wave breaking injects a spray of C/O into the superincumbent H/He.

In the absence of enrichment prior to ignition, the base of the convective zone, does not reach the C/O interface. As a result, there is no additional mixing, and the runaway is slow. In contrast, the formation of a mixed layer during the accretion of H/He, prior to ignition, causes a more violent runaway. The envelope can be enriched by $\leq 25\%$ of C/O by mass (consistent with that observed in some ejecta) for shear velocities, over the surface, with Mach numbers $\leq 0.4$. 
Fig. 1.—Breaking C/O waves, as determined by simulations in two dimensions. Gravity points toward the bottom of the figure, with the vertical distance $y$ in units of the pressure scale height $H$, as evaluated just above the interface. The color scale indicates the mass density in units of g cm$^{-3}$.
Fig. 4.—Kippenhahn diagram of a nova without enrichment. The x-axis indicates time intervals for the different evolution stages, and the y-axis gives the mass above the C/O WD substrate. Green hatching (framed by a green line) indicates convection, blue shading indicates nuclear energy generation, for which each level of darker blue denotes an increase by 1 order of magnitude, starting at $10^{10}$ ergs g$^{-1}$ s$^{-1}$. The thick black line shows the total mass of the star (including ejecta), increasing through accretion; the dash-dotted line indicates the mass outside of $10^{15}$ cm; and the dashed line marks the interface between the C/O WD substrate and the accreted layers.
The underlying white dwarf

White dwarfs are the endpoints of the stellar evolution of stars with masses below 11-12 $M_\odot$.

- $M \leq 8-10 \, M_\odot \rightarrow$ CO white dwarfs (He burning)
- $8-10 \, M_\odot \leq M \leq 12 \, M_\odot \rightarrow$ ONe white dwarfs (C burning)

$10 \, M_\odot \rightarrow 1.2 \, M_\odot$ ONe core
The underlying white dwarf

10\(M_\odot\) mass Population I star evolved from the H-burning main sequence through carbon burning

1.2\(M_\odot\) ONe core

\(\neq\)

ONeMg core predicted by hydrostatic C-burning (Arnett & Truran, 1969)


see also Domínguez, Tornambè & Isern 1993

Fig. 7.—Abundances by mass of the major isotopes in the helium-exhausted interior at the end of the carbon-burning phase \((t = 7.1895212 \times 10^{14}\) s).
The underlying white dwarf

Size of the CO core at the beginning of C burning, for single and binary evolution

Mass point at which C is ignited

Minimum mass required for C-ignition to take place (*): 8.1 M\(_\odot\) (single) and 8.7 M\(_\odot\) (binary)

Off-center C-ignition

Central C ignition:

\[
\begin{cases} 
11 \ M_\odot & \text{for single evolution} \\
12 \ M_\odot & \text{for binary evolution}
\end{cases}
\]

Be careful when adopting \(M>8M_\odot\) as “massive stars”

Gil Pons, García-Berro, José, Hernanz & Truran, 2003, A&A
The underlying white dwarf

Fig. 3. Size of the final cores as a function of the ZAMS mass for single and binary star evolution.

Size of the final core for single and binary evolution: relevance of new $M_{\text{initial}}$-$M_{\text{final}}$ mass relation for the fraction of novae hosting ONe white dwarfs: smaller number but still around 30%

Gil-Pons, García-Berro, José, Hernanz, Truran, 2003, A&A
The underlying White Dwarf

**Fig. 6.** Number abundances of the CO core resulting from $9 \, M_\odot$ ZAMS primary component in a CBS.

**Fig. 5.** Number abundances of the uppermost regions of an ONe white dwarf resulting from the evolution of a $10 \, M_\odot$ ZAMS primary component in a close binary system.

“CO buffer” on top of an ONe core

*(Gil-Pons et al., 2003, A&A)*
The underlying White Dwarf

CO buffer on top of ONe core: weird nuclesoynthesis potentially leading to missclassification of novae

The underlying White Dwarf

Relevance of CO buffer on top of ONe WD for nova nucleosynthesis: lack of Ne in the ejecta: misclassification of novae (non-Ne nova ≠ CO nova)
Relevance of nucleosynthesis in classical novae

- interpretation of elemental abundances observed in individual objects
- chemical evolution of the Galaxy
- presolar meteoritic grains ↔ dust formation in novae (IR obs.)
- gamma-ray emission
## Models versus Observations of Some Classical Nova Systems

**V693 CrA 1981**

<table>
<thead>
<tr>
<th>Model</th>
<th>H</th>
<th>He</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>Ne</th>
<th>Na–Fe</th>
<th>Z</th>
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<tbody>
<tr>
<td>Vanlandingham et al. 1997</td>
<td>0.25</td>
<td>0.43</td>
<td>0.025</td>
<td>0.055</td>
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<td>0.045</td>
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<td>0.065</td>
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<tr>
<td>Andréa et al. 1994</td>
<td>0.16</td>
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<td>0.051</td>
<td>0.28</td>
<td>0.26</td>
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<td>Williams et al. 1985</td>
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<td>0.0046</td>
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<td>0.18</td>
<td>0.071</td>
<td>0.50</td>
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**V1370 Aql 1982**

<table>
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<tr>
<th>Model</th>
<th>H</th>
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<th>C</th>
<th>N</th>
<th>O</th>
<th>Ne</th>
<th>Na–Fe</th>
<th>Z</th>
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<tr>
<td>Andréa et al. 1994</td>
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<td>0.24</td>
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**QU Vul 1984**

<table>
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<th>H</th>
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<th>C</th>
<th>N</th>
<th>O</th>
<th>Ne</th>
<th>Na–Fe</th>
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<td>0.36</td>
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<td>0.037</td>
<td>0.090</td>
<td>0.0035</td>
<td>0.25</td>
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**PW Vul 1984**

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<th>O</th>
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<td>Andréa et al. 1994</td>
<td>0.47</td>
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<td>0.0036</td>
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**V1688 Cyg 1978**

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<th>Ne</th>
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<td>0.073</td>
<td>0.094</td>
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<td>0.0036</td>
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<td>0.13</td>
<td>0.0038</td>
<td>0.0015</td>
<td>0.28</td>
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</table>

Nova nucleosynthesis and chemical evolution of the Galaxy

\[ M_{\text{ejec}}(\text{theor.}) \sim 2 \times 10^{-5} \ M_\odot/\text{nova} \]

\[ R(\text{novae}) \sim 35 \ \text{novae/yr} \]

\[ \text{Age of the Galaxy} \sim 10^{10} \ \text{yrs} \]

\[ M_{\text{ejec,total}}(\text{novae}) \sim 7 \times 10^6 \ M_\odot = (7 \times 10^{-4} \ M_\odot/\text{yr}) \approx 1/3000 \ M_{\text{gal}}(\text{gas+dust}) \]

*Novae can account for the galactic abundances of the isotopes they overproduce (w.r.t. sun) by factors \( \geq 3000 \)*
Novae nucleosynthesis: overproductions w.r.t. solar
Novae nucleosynthesis: overproductions w.r.t. solar
Novae nucleosynthesis: overproductions w.r.t. solar

ONe

1.35M☉
The galactic lithium evolution revisited*

D. Romano1,2, F. Matteucci2,1, P. Molaro2, and P. Bonifacio2
1 SISSA/ISAS, Via Beirut 2–4, 34014 Trieste, Italy
2 Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, 34131 Trieste, Italy

Received 26 April 1999 / Accepted 5 October 1999

In order to reproduce the upper envelope of the A(Li) vs [Fe/H] diagram we need to take into account several stellar Li sources: AGB stars, Type II SNe and novae. In particular, novae are required to reproduce the steep rise of A(Li) between the formation of the Solar System and the present time, as is evident from the data we sampled. On the other hand, 7Li yields for SNeII should be lowered by at least a factor of two in order to reproduce the extension of the Spite plateau.

7Li

CNO: 13C, 15N, 17O

See as well Alibés, Labay & Canal, 2001, A&A

Nova nucleosynthesis and Galactic evolution of the CNO isotopes

MNRAS, 2004

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2 INAF, Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, I-34131 Trieste, Italy
3 Dipartimento di Astronomia, Università di Trieste, Via G.B. Tiepolo 11, I-34131 Trieste, Italy

In this paper, we adopt detailed nucleosynthesis in the ejecta of classical novae as published by José & Hernanz (1998) for a grid of hydrodynamical nova models spanning a wide range of CO and ONe WD masses (0.8–1.35 M☉) and mixing levels between the accreted envelope and the outermost shells of the underlying WD core (25%–75%). We find that, when included in a detailed model for the chemical evolution of the Milky Way, they produce 12C/13C, 14N/15N and 16O/17O ratios decreasing with increasing metallicity, i.e., decreasing with time at the solar radius and increasing with Galactic distance at the present time, in agreement with the trends inferred from observations. However, if novae are...
**Dust in novae**

*IR observations indicate that dust grains are formed in many novae*

Nova Cyg 1978
Novae and presolar meteoritic grains

Primitive meteorites contain presolar grains, which condensed in stellar atmospheres or in supernova or nova ejecta, and survived their “interstellar trip” and solar system formation.

Isotopic abundances measurements in lab allow to ascertain their origin.
Novae and presolar meteoritic grains

Five SiC and two graphite grains from the Murchison and Acfer 094 meteorites show isotopic compositions indicating a nova origin: Amari, Gao, Nittler, Zinner, José, Hernanz & Lewis (2001); José, Hernanz, Amari, Lodders & Zinner (2004)
Novae and presolar meteoritic grains

Amari et al. 2001
Main radioactive isotopes synthesized in classical novae

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$\tau$</th>
<th>Type of emission</th>
<th>Nova type</th>
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<tbody>
<tr>
<td>$^{13}\text{N}$</td>
<td>862 s</td>
<td>511 keV line, continuum (E&lt;511 keV)</td>
<td>CO and ONe</td>
</tr>
<tr>
<td>$^{18}\text{F}$</td>
<td>158 min</td>
<td>511 keV line, continuum (E&lt;511 keV)</td>
<td>CO and ONe</td>
</tr>
<tr>
<td>$^{7}\text{Be}$</td>
<td>77 days</td>
<td>478 keV line</td>
<td>CO mainly</td>
</tr>
<tr>
<td>$^{22}\text{Na}$</td>
<td>3.75 yr</td>
<td>1275 keV line</td>
<td>ONe</td>
</tr>
<tr>
<td>$^{26}\text{Al}$</td>
<td>$1.0\times10^6$ yr</td>
<td>1809 keV line</td>
<td>ONe</td>
</tr>
</tbody>
</table>
Spectra of CO and ONe novae

\[ M_{\text{WD}} = 1.15 \, M_\odot \]

Light curves: 1275 keV $^{22}\text{Na}$ line

**Rise phase**

- $t_{\text{max}}$: 20 days (1.15$M_\odot$), 12 days (1.25 $M_\odot$), line width $\sim$ 20 keV; duration: months
- Flux (max) $\sim 2 \times 10^{-5}$ ph/cm$^2$/s; $M_{\text{ejected}}(^{22}\text{Na}) \sim (6-7) \times 10^{-9} M_\odot$

**Only in ONe novae**

- $d=1$ kpc

**Exponential decline**

- Predicted theoretically by Clayton & Hoyle, 1974
Observations : 1275 keV line ($^{22}$Na)

CGRO/COMPTEL searched for 1275 keV emission in many novae: no detection, upper limits

CGRO/COMPTEL most constraining upper limit (Nova Cyg 1992, $d=2.3$ kpc) in agreement with current theoretical predictions:

$$F < 2.3 \times 10^{-5} \text{phot/cm}^2/\text{s} \Rightarrow M_{ej}(^{22}\text{Na}) < 3.0 \times 10^{-8} M_\odot$$

Ilyudin et al. 1995, A&A
Nuclear uncertainties: 1275 keV (\(^{22}\text{Na}\)) line

Uncertainties in the rates \(^{21}\text{Na}(p,\gamma)^{22}\text{Mg}\) and \(^{22}\text{Na}(p,\gamma)^{23}\text{Mg}\) translated into uncertainties by factors around 3 in the \(^{22}\text{Na}\) yields (José, Coc & Hernanz, 1999) – and therefore in the flux of the 1275 keV line.

These uncertainties have been *reduced* by recent measurements:

Jenkins et al 2004: \(^{22}\text{Na}(p,\gamma)^{23}\text{Mg}\)

Bishop et al. 2003, D’Auria et al. 2004: \(^{21}\text{Na}(p,\gamma)^{22}\text{Mg}\)
Galactic distribution of $\gamma$-ray emission from novae

Theoretical predictions: Jean, Hernanz, Gómez-Gomar, José, 2000, MNRAS

Light curves: 478 keV ($^7$Be) line

- Only in CO novae
- $t_{\text{max}}$: 13 days (0.8$M_{\odot}$)
- 5 days (1.15 $M_{\odot}$)
- duration: some weeks
- Flux $\sim (1-2)\times10^{-6}$ ph/cm$^2$/s
- $M_{\text{ejected}}(^7\text{Be}) \sim (0.7-1.1)\times10^{-10}M_{\odot}$
- Line width: 3-7 keV

predicted theoretically by Clayton 1981
Light curves: 511 keV line

In CO and ONe novae

<table>
<thead>
<tr>
<th>Model</th>
<th>$t_{\text{max}}$ (h)</th>
<th>$F_{\text{max}}$ (ph/cm²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO, 0.8 $M_\odot$</td>
<td>- - -</td>
<td>$2.6 \times 10^{-5}$</td>
</tr>
<tr>
<td>CO, 1.15 $M_\odot$</td>
<td>6.5</td>
<td>$5.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>ONe, 1.15 $M_\odot$</td>
<td>6</td>
<td>$1.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>ONe, 1.25 $M_\odot$</td>
<td>5</td>
<td>$1.9 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

- 511 keV line in ONe novae remains after 2 days until $\sim$ 1 week because of $e^+$ from $^{22}\text{Na}$
- Intense (but short duration)
- Very early appearance, before visual maximum (i.e., before discovery)

d=1 kpc
Nuclear uncertainties related with 18F synthesis (511 keV & continuum emission)

Rates obtained including the latest experimental data up to the end of 1999

Coc, Hernanz, José, Thibaud, 2000, A&A
Nuclear uncertainties related with $^{18}$F synthesis (511 keV & continuum emission)

Uncertainties in the $^{18}$F yields reduced by a factor of ~5 ($^{18}$F+p) and by a factor of ~3 ($^{17}$O+p) in the nova T range

$^{18}$F(p,α)$^{15}$O
- Other measurements: Bardayan et al.; Kozub et al.: rates 3-5 times lower than expected

$^{17}$O(p,γ)$^{18}$F - $^{17}$O(p,α)$^{14}$N
- Fox et al. 2004: uncertainties reduced
- Orsay results: less $^{17}$O, less $^{18}$F

First CARINA Workshop, 8-10 June 2005, Aiguablava
End point of nova nucleosynthesis: $^{40}\text{Ca}$
Main nuclear path

José & Moreno (2002)

rp process on X-ray bursts

T=3$\times$10$^8$ K

T=6$\times$10$^8$ K

T=10$^9$ K

T=1.7$\times$10$^9$ K
End Point of the $r p$ Process on Accreting Neutron Stars

H. Schatz,¹ A. Aprahamian,² V. Barnard,² L. Bildsten,³ A. Cumming,³ M. Ouellette,¹ T. Rauscher,⁴ F.-K. Thielemann,⁴ and M. Wiescher²

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We calculate the rapid proton ($r p$) capture process of hydrogen burning on the surface of an accreting neutron star with an updated reaction network that extends up to Xe, far beyond previous work. In both steady-state nuclear burning appropriate for rapidly accreting neutron stars (such as the magnetic polar caps of accreting x-ray pulsars) and unstable burning of type I x-ray bursts, we find that the $r p$ process ends in a closed SnSbTe cycle. This prevents the synthesis of elements heavier than Te and has important consequences for x-ray burst profiles, the composition of accreting neutron stars, and potentially galactic nucleosynthesis of light $p$ nuclei.
New Approach for Measuring Properties of $rp$-Process Nuclei

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A new experimental approach was developed that can reduce the uncertainties in astrophysical rapid proton capture ($rp$) process calculations due to nuclear data. This approach utilizes neutron removal from a radioactive ion beam to populate the nuclear states of interest. Excited states were deduced by the $\gamma$-decay spectra measured in a semiconductor Ge-detector array. In the first case studied, $^{33}\text{Ar}$, excited states were measured with uncertainties of several keV. The 2 orders of magnitude improvement in the uncertainty of the level energies resulted in a 3 orders of magnitude improvement in the uncertainty of the calculated $^{32}\text{Cl}(p, \gamma)^{33}\text{Ar}$ rate that is critical to the modeling of the $rp$ process. This approach has the potential to measure key properties of almost all interesting nuclei on the $rp$-process path.
Mass Measurement on the $r p$-Process Waiting Point $^{72}$Kr


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The mass of one of the three major waiting points in the astrophysical $r p$ process $^{72}$Kr was measured for the first time with the Penning trap mass spectrometer ISOLTRAP. The measurement yielded a relative mass uncertainty of $\delta m/m = 1.2 \times 10^{-7}$ ($\delta m = 8$ keV). $^{73,74}$Kr, also needed for astrophysical calculations, were measured with more than 1 order of magnitude improved accuracy. We use the ISOLTRAP masses of $^{72-74}$Kr to reanalyze the role of $^{72}$Kr ($T_{1/2} = 17.2$ s) in the $r p$ process during x-ray bursts and conclude that $^{72}$Kr is a strong waiting point delaying the burst duration with at least 80% of its $\beta$-decay half-life.
We review the origin and evolution of the heavy elements, those with atomic numbers greater than 30, in the early history of the Milky Way. There is a large star-to-star bulk scatter in the concentrations of heavy elements with respect to the lighter metals, which suggests an early chemically unmixed and inhomogeneous Galaxy. The relative abundance patterns among the heavy elements are often very different from the solar system mix, revealing the characteristics of the first element donors in the Galaxy. Abundance comparisons among several halo stars show that the heaviest neutron-capture elements (including barium and heavier) are consistent with a scaled solar system rapid neutron-capture abundance distribution, whereas the lighter such elements do not conform to the solar pattern. The stellar abundances indicate an increasing contribution from the slow neutron-capture process (s-process) at higher metallicities in the Galaxy. The detection of thorium in halo and globular cluster stars offers a promising, independent age-dating technique that can put lower limits on the age of the Galaxy.

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Fig. 1. A chart of the nuclides [after (37)]. At a given proton (atomic) number, isotopes toward the left are proton rich, and those to the right are the neutron-rich ones that are the subject of this article. The stable nuclides are marked by black boxes; n-capture in s-process synthesis occurs near these nuclei close to the "valley of β-stability." The jagged diagonal black line represents the limit of experimentally determined properties of nuclei, and the magenta line represents the r-process "path." Vertical and horizontal black lines represent closed neutron or proton shells, sometimes referred to as "magic numbers." Color shading denotes the different (log) time scales for β-decay.
Abundance comparison of elements in the UMP halo star CS 22892-052 (points with error bars) and a scaled solar system r-process abundance curve. The colored line is based on nuclear physics (i.e., neutron capture cross section) experiments to determine the solar system s- and process isotopic (see Fig. 3), and hence elemental, abundance determinations.