r-Process Nucleosynthesis in v-Driven Winds

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Story I

- After running out of fuel, a massive star undergoes gravitational collapse.
- Shockwave bounces off core leaving the hot proto-neutron star behind.
- The neutron star cools through neutrino emission.
• The neutrinos deposit a sufficient amount of energy in the matter surrounding the neutron star to create a \( \nu \)-driven wind

• \( r \)-Process nucleosynthesis occurs in the wind

• The properties of the wind are determined by the mass, the radius, and the properties of the \( \nu \) emission.
Story III

The wind evolves dynamically!

- We want to calculate the properties of the wind without a complicated hydrodynamic calculation.
- Mimic the behavior of the inner boundary – mass outflow rate vanishes near the neutrinosphere.

Adapted from Qian, Woosley '96

![Graph showing entropy, neutrino specific heating rate, and mass outflow rate over the v-sphere range from 10 to 200.

Neutron star

Injection Region

Wind region – Mass outflow Rate is approximately constant

Unshocked Matter

Shockwave

- Entropy
- Neutrino specific heating rate
- Mass outflow rate

\[ \dot{q} / 10^{20} \text{ erg g}^{-1} \text{ s}^{-1} \]

\[ M / 10^{-5} \text{ M}_\odot \text{ s}^{-1} \]
Outline

• Neutrino-driven wind
  – Injection region vs. wind region
  – Comparison with hydrodynamics

• Nucleosynthesis
  – Neutron to seed ratios

• Conclusions and Outlook
r-Process Nucleosynthesis - Motivation

- Present state of the field
  - Still difficult to produce $A \sim 130$ and 195 peaks
  - Neutrino-driven with is still arguably the preferred site
- Goal:
  - Injection region - Boundary conditions near the neutron star are automatically determined, not fixed a priori.
  - Connection with hydrodynamics – ensure that the procedure is sufficiently accurate to reproduce more involved calculations.
  - Self-consistency - Neutron to seed ratio tracks the evolution of the wind as the neutrinos flow out.
Injection Region

- Definition: Matter near neutron star which is in hydrostatic equilibrium and kinetic equilibrium, i.e. $\dot{q} = 0$
- Fix boundary by the condition $\gamma \varepsilon_{NR} = \varepsilon_R \cdot (\gamma \sim 1)$
- This condition automatically gives $\frac{\varepsilon}{\dot{q}_{\text{heating}}} = \tau_q \sim \tau_{\text{dyn}} = \frac{r}{\nu}$

at both early and late times. Equilibrium is lost because neutrinos cannot heat matter as fast as it flows outward.
Minimum Attainable Pressure

- In the 10km case, the injection region is further limited by the minimum attainable pressure
  - Temperature is strongly determined by the kinetic equilibrium condition
  - Density and pressure must decrease exponentially since we are in hydrostatic equilibrium.
  - Curves of pressure at fixed $q$ are plotted at different radii
  - At $r=11.8$ km, the pressure reaches the minimum and we cannot maintain equilibrium.
Analytical Treatment of the Interface

• Utilizing our condition for the boundary between the injection region and the wind region one can approximate the transition density:

\[ \rho_{\text{int}} = 3 \times 10^8 \varepsilon_{\nu_e,\text{MeV}} L_{\nu_e,51}^{1/2} \frac{\text{g}}{\text{cm}^3} \]

• Similar expressions for other quantities
• The expressions agree with the exact results to within 25 percent
Comparison with Sumiyoshi, et. al. (1999) and Terasawa, et. al. (2002)

<table>
<thead>
<tr>
<th>$P_{out}$ [dyn/cm$^2$]</th>
<th>$\tau_{dyn}$ [sec]</th>
<th>$S$ [k$B$]</th>
<th>$Y_{e,i}$</th>
<th>$T_{out}$ [10$^3$K]</th>
<th>$Y_{\alpha,out}$</th>
<th>$Y_{\alpha,seed,out}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{20}$</td>
<td>$2.32 \times 10^{-2}$</td>
<td>200</td>
<td>0.43</td>
<td>0.4</td>
<td>0.196</td>
<td>$9.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>$10^{21}$</td>
<td>$2.54 \times 10^{-2}$</td>
<td>180</td>
<td>0.43</td>
<td>0.7</td>
<td>0.189</td>
<td>$2.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>$10^{22}$</td>
<td>$3.34 \times 10^{-2}$</td>
<td>170</td>
<td>0.44</td>
<td>1.3</td>
<td>0.174</td>
<td>$2.4 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

- Terasawa, et. al predicts a larger entropy than other calculations of the neutrino driven wind.
- This entropy is sensitive to the initial temperature (cooling by electron capture $\sim T^6$).
- A lower initial temperature could easily produce this discrepancy in the final properties of the wind.
- How is a lower temperature consistent with the notion of an injection region?
Neutrino-Driven Wind Results

- Our results agree with hydrodynamical calculations to within 10 percent.
- Varying $\gamma$ by a factor of 3 in each direction does not strongly affect the results.
- The effects of GR are consistent with Cardall and Fuller.
- A modification of the neutrino interactions by as much as a factor of 4 doesn’t make a strong modification of the results.
- Removing the injection region results in a 20-40% modification of the properties of matter relevant for nucleosynthesis.
Nucleosynthesis

• Initially, no protons – just n, α
• $^9\text{Be}$ is created from α through $^4\text{He}(\alpha n,\gamma)^9\text{Be}$
  – Q small implies equilibrium: $Y_9 \sim C Y_\alpha^2 Y_n$
• From $^9\text{Be}$, $^{12}\text{C}$ is made through $^9\text{Be}(\alpha,n)^{12}\text{C}$
• Further reactions initially prohibited by $^{12}\text{C}(\gamma,2\alpha)^4\text{He}$
• Begin when the rate of $^{12}\text{C}(\gamma,2\alpha)^4\text{He}$ is equal to that of $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ at $T_9=5$
• Stop at $T_9=2.5$ where Coulomb barrier sets in and only neutron capture is allowed.

$$\frac{dY_{\text{seed}}}{dt} = Y_\alpha Y_9 \rho \lambda(^9\text{Be}, \alpha)$$

• $Y_{\text{seed}}$ is the number fraction of a nucleus with fixed $\bar{A}$ and $\bar{Z}$.
• Consistently include the time dependence of entropy, density, temperature, and electron fraction from wind. This includes the “alpha-effect” (Fuller and Meyer 1995, McLaughlin, Fuller, and Wilson 1996).
r-Process – Results

- 3 Different scenarios
  - I. Highly luminous star with higher average energies and equipartition ($E_{\nu e} \sim 14$)
  - II. Cooled, less luminous configuration ($E_{\nu e} \sim 9$)
  - III. Cool deleptonized configuration with equal flux

- N/S ratios of 40 or 105 necessary to produce $A \sim 130$ or $A \sim 195$ peaks
- $E_{\nu e} > 18$ MeV necessary for $A \sim 130$ peak.
Conclusion and Outlook

• We have constructed self-consistent solutions for the neutrino-driven wind
  – The inner boundary conditions are physically connected to the creation of the wind
  – Our results match hydrodynamic calculations to within 10 percent
• The corresponding neutron to seed ratios still do not easily provide for nucleosynthesis at the $A\sim130$ and $A\sim190$ r-process peaks.
• Our technique allows a direct connection between neutron star properties obtainable in a supernova calculation and to r-process nucleosynthesis through the neutron to seed ratios.