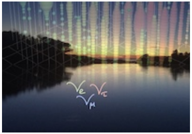
νp-process in neutrino-driven outflows in core-collapse supernovae

Amol V. Patwardhan

(w/ Payel Mukhopadhyay and Alex Friedland)

March 31, 2022



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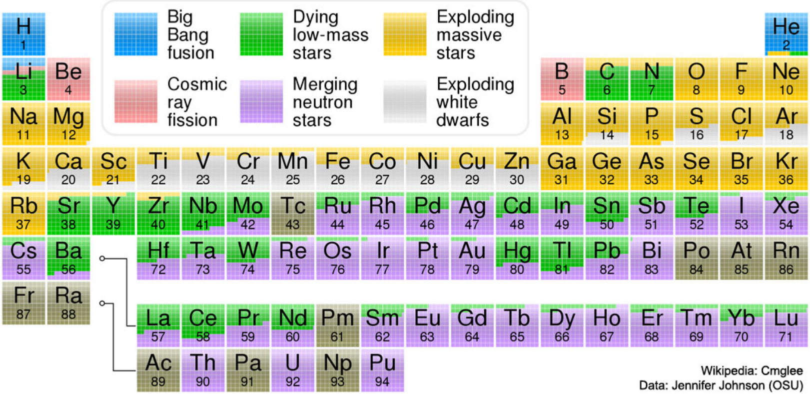
The origin of the elements



Wikipedia: Cmglee
Data: Jennifer Johnson (OSU)

Figure: Astronomy picture of the day (2020 August 9)

The origin of the elements

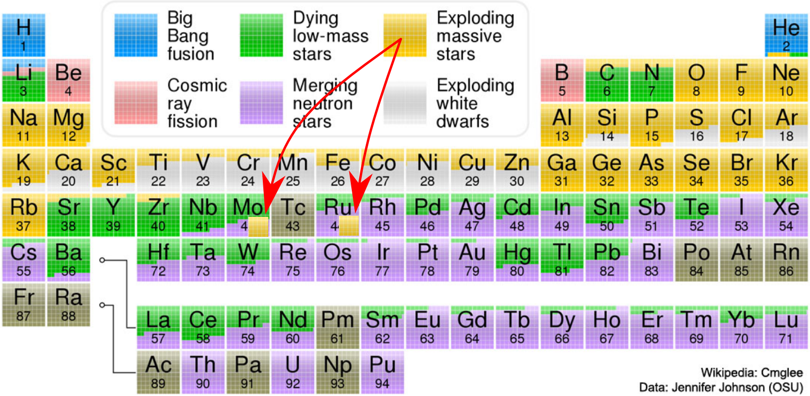


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Chart of the nuclides

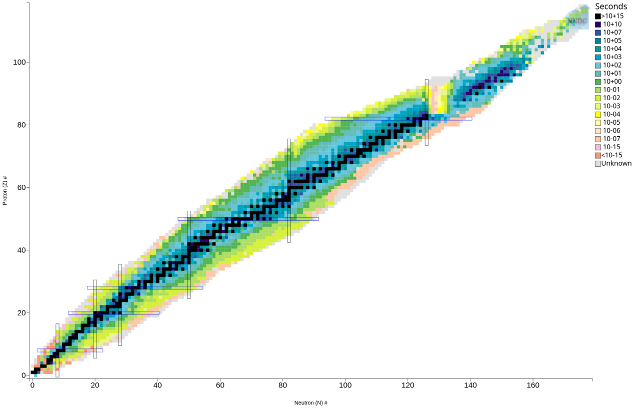

Figure: Chart of Nuclides - National Nuclear Data Center

Chart of the nuclides

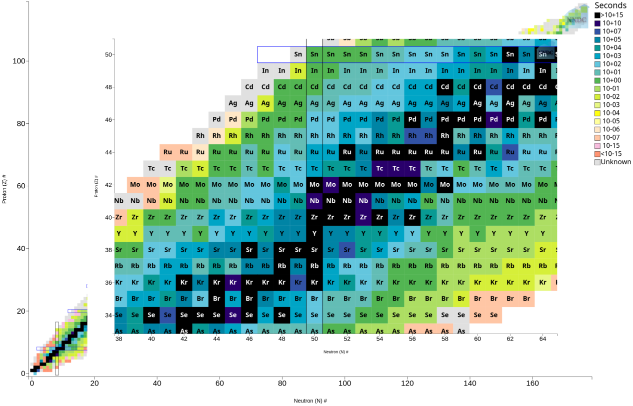

Figure: Chart of Nuclides - National Nuclear Data Center

Outline

1. Proton rich nucleosynthesis
2. νp-process nucleosynthesis
3. The reported difficulties with the νp-process
4. The resolution — hydrodynamics!

p-rich nucleosynthesis does not happen easily!

- Case in point — early universe ($S \sim 10^{10}$)
  - Freeze-out from nuclear statistical equilibrium (NSE) at $T \approx 0.1$ MeV leads to α-particle formation
  - Coulomb barriers inhibit proton capture at $T < 0.1$ MeV
  - In our boring p-rich universe, only α-particles are made (and traces of ^{2}H, ^{3}He, ^{7}Li)
  - In a hypothetical early universe with more neutrons than protons (e.g., if m_n were less than m_p), BBN could probably make heavier elements through neutron captures

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- $\mathcal{Q}$. What would happen if the early universe (or some sub-regions of it) had a much lower entropy ($S \sim 100$)?

Nonetheless, p-rich heavy elements do exist in nature

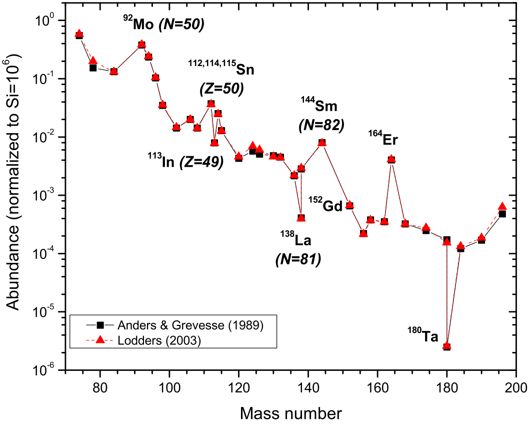

Figure: Abundances of various p-nuclides (T. Rauscher *et al.*, Rep. Prog. Phys. 76 (2013) 066201). See also: Katharina Lodders, Astrophys. J. 591 (2003) 1220–1247.

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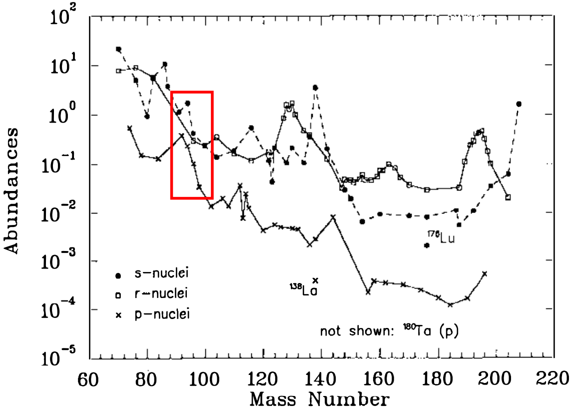

Figure: The solar system abundances of r-nuclei, s-nuclei, and p-nuclei (B. S. Meyer, Annu. Rev. Astron. Astrophys. 1994. 32: 153–190). Most p-nuclides have abundances 1–2 orders of magnitude lower than nearby s- and r-process (neutron-rich) nuclides. Except for ^{92,94}Mo and ^{96,98}Ru.

Nonetheless, p-rich heavy elements do exist in nature

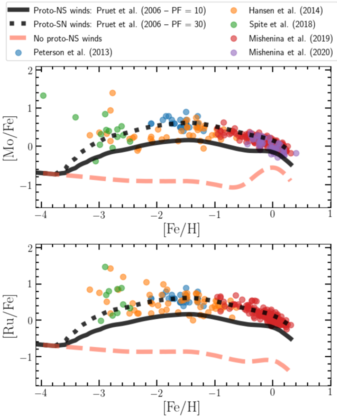

Figure: Observed abundances of [Mo/Fe] and [Ru/Fe] in metal poor stars, and predicted abundances for a p-rich proto-NS wind model from Pruet *et al.* (2006), as a function of metallicity [Fe/H] (F. Vincenzo *et al.*, MNRAS 508, 3499–3507 (2021)). Note the scatter at low metallicities.

p-process mechanisms [Rauscher *et al.* (2013)]

- γ-process (Woosley and Howard, 1978, ApJS 36, 285)
  - Photodisintegration of neutron rich isotopes either via (γ, n) or via $(\gamma, p)/(\gamma, \alpha)$ + β-decays
  - Occurs during explosive O/Ne shell burning in massive stars, or in exploding white dwarfs (type-1a supernovae)
  - Can make some ^{92}Mo but underproduces ^{94}Mo and ^{96,98}Ru
- ν-process (Woosley *et al.*, ApJ, 356, 272 (1990); Fuller and Meyer, ApJ 453, 792 (1995))
  - Neutrino captures on stable nuclei
  - May occur in core-collapse supernova environments where ν fluxes large enough to offset small cross-sections
  - Outflowing material must remain in close proximity to NS for significant length of time — difficult to implement

p-process mechanisms

- rp-process (Schatz *et al.*, Phys. Rept. 294, 167–263 (1998); L. Bildsten, astro-ph/9709094)
  - Rapid proton capture followed by β^+ decays
  - Occurs on the surface of accreting neutron stars where thermonuclear H/He burning drives up temperatures enough for a short amount of time to overcome Coulomb repulsion
  - Hindered by β^+ decay "waiting points" along the nucleosynthesis chain
- α-process (Hoffman *et al.* ApJ, 460, 478 (1996))
  - Proceeds via chain of α, n, and p captures following α-rich freezeout in neutrino-driven outflows with $Y_e \sim 0.48$–0.49
  - Can make ^{92}Mo but not much ^{94}Mo or ^{96,98}Ru
  - Makes appreciable amounts of ^{92}Nb (comparable to ^{92}Mo)

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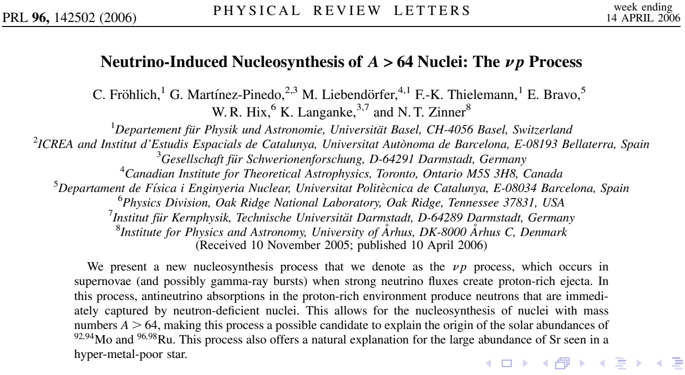
What about ^{92,94}Mo and ^{96,98}Ru?

- None of the aforementioned processes can explain their anomalously high abundances
- New mechanism proposed in 2005: the νp-process



PRL **96,** 142502 (2006) PHYSICAL REVIEW LETTERS week ending 14 APRIL 2006

Neutrino-Induced Nucleosynthesis of $A > 64$ Nuclei: The νp Process

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We present a new nucleosynthesis process that we denote as the νp process, which occurs in supernovae (and possibly gamma-ray bursts) when strong neutrino fluxes create proton-rich ejecta. In this process, antineutrino absorptions in the proton-rich environment produce neutrons that are immediately captured by neutron-deficient nuclei. This allows for the nucleosynthesis of nuclei with mass numbers $A > 64$, making this process a possible candidate to explain the origin of the solar abundances of ^{92,94}Mo and ^{96,98}Ru. This process also offers a natural explanation for the large abundance of Sr seen in a hyper-metal-poor star.

The νp-process

- See also: Pruet *et al.*, ApJ 644, 1028 (2006);
  S. Wanajo, ApJ 647, 1323 (2006)
- Can occur in proton-rich neutrino driven outflows in a core-collapse supernova environment
- $\bar{\nu}_e$ capture on free protons creates a sub-dominant population of neutrons, which can help bypass the β^+ decay waiting points on the rp-process chain through (n,p) reactions [or via (n,γ) + (p,γ)]. νp-process is therefore also called "neutrino-induced rp-process" (Wanajo, 2006)

Physics of the νp-process

Wanajo *et al.*, ApJ 729 46 (2011)

- Seed nuclei up to ^{56}Ni are formed via freeze-out from nuclear quasi-equilibrium as the outflow cools to $T \sim 3\,$GK
- $\bar{\nu}_e$ capture on free protons (in a p-rich wind) creates a subdominant neutron population ($Y_n \sim 10^{-12}$–10^{-11}), triggering (n,p) and (n,γ) reactions to bypass the β^+ decay waiting points. These, combined with (p,γ), keep the flow moving along the rp chain for $3\,\text{GK} > T > 1.5\,\text{GK}$
- At $T \lesssim 1.5\,$GK, Coulomb barriers inhibit further (p,γ) reactions, and the νp-process ends

Favourable conditions for νp-process

Wanajo *et al.*, ApJ 729 46 (2011)

1. Short time interval (τ_1) for $T > 3\,$GK
2. High entropy-per-baryon ($S \gtrsim 70$) in the outflow
3. Long time interval (τ_2) in the $3\,\text{GK} > T > 1.5\,$GK band

(1) and (2) facilitate a high proton-to-seed ratio at the onset of the νp-process, and (3) leads to a larger integrated $\bar{\nu}_e$ fluence, furnishing more neutrons to drive the reaction flow towards higher mass numbers

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Reproducing solar abundances and observed ratios

- "...the relative production of ^{92}Mo and ^{94}Mo is set by a competition governed by the proton separation energy of ^{93}Rh. ...It is found that for the conditions calculated in recent two-dimensional supernova simulations, and also for a large range of outflow characteristics around these conditions, the solar ratio of ^{92}Mo to ^{94}Mo cannot be achieved"
  — J. L. Fisker *et al.*, 2009 ApJ 690 L135

- "...we find that proton-rich winds can make dominant contributions to the solar abundance of ^{98}Ru, significant contributions to those of ^{96}Ru ($\lesssim 40\%$) and ^{92}Mo ($\lesssim 27\%$), and relatively minor contributions to that of ^{94}Mo ($\lesssim 14\%$) ...In conclusion, our results strongly suggest that the solar abundances of ^{92,94}Mo are dominantly produced by sources other than the neutrino-driven wind"
  — J. Bliss *et al.*, 2018 ApJ 866 105

The Niobium puzzle

- Another p-rich nucleus, ^{92}Nb, is also known to occur in nature, but cannot be made in the νp-process — shielded from p-rich nuclear flows by the neighboring stable ^{92}Mo

- Can be made in the γ-process — production ratio of ^{92}Nb/^{92}Mo, convolved with suitable models for galactic chemical evolution (GCE) and ISM mixing, is roughly consistent with the inferred ratio in the early solar system

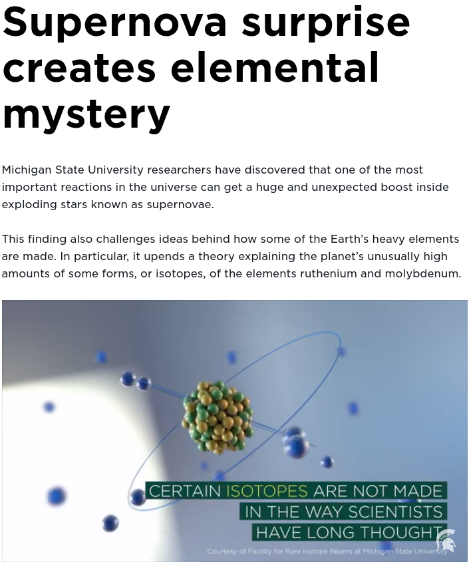
- This is used as an argument that any process that produces the bulk of ^{92}Mo must also produce ^{92}Nb concurrently, thereby putting the νp process in doubt [Rauscher *et al.* (2013)]

- However: (i) considerable uncertainties in both the production and the inferred early solar system ratios of ^{92}Nb/^{92}Mo, and (ii) consistency between ratios doesn't preclude two separate processes from being dominant sources of ^{92}Nb and ^{92}Mo respectively

The triple-alpha crisis

- It was pointed out (S. Wanajo *et al.*, 2011 ApJ 729 46) that uncertainties in the triple-α reaction rate could have implications for νp-process yields
- M. Beard *et al.* [PRL 119, 112701 (2017)] calculated the in-medium triple-α enhancement, and subsequently Jin et al. [Nature vol. 588, pg. 57–60 (2020)], incorporated these into their calculations of the νp-process
- "The resulting suppression of heavy-element nucleosynthesis for realistic conditions casts doubt on the νp process being the explanation for the anomalously high abundances of ^{92,94}Mo and ^{96,98}Ru isotopes in the Solar System . . . "

Elemental mystery



Supernova surprise creates elemental mystery

Michigan State University researchers have discovered that one of the most important reactions in the universe can get a huge and unexpected boost inside exploding stars known as supernovae.

This finding also challenges ideas behind how some of the Earth's heavy elements are made. In particular, it upends a theory explaining the planet's unusually high amounts of some forms, or isotopes, of the elements ruthenium and molybdenum.

CERTAIN ISOTOPES ARE NOT MADE IN THE WAY SCIENTISTS HAVE LONG THOUGHT

Courtesy of Facility for Rare Isotope Beams at Michigan State University

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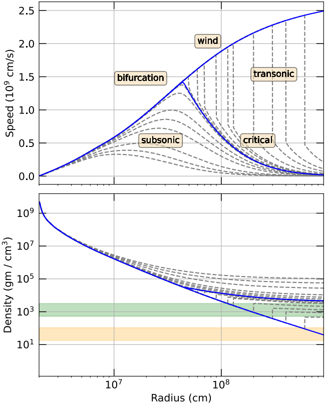
Hydrodynamics of neutrino driven ouflows

Neutrino driven outflows can be supersonic or subsonic. In fact, in typical core-collapse supernova environments, they are often near-critical and therefore sensitive to the precise boundary conditions (A. Friedland and P. Mukhopadhyay, arxiv:2009.10059).



Semi-analytic outflow model

- Steady-state outflow equations (Qian and Woosley, ApJ 471 (1996) 331-351):

$$\dot{M} = 4\pi r^2 \rho v, \tag{1}$$

$$v\frac{dv}{dr} = -\frac{1}{\rho}\frac{dP}{dr} - \frac{GM}{r^2}, \tag{2}$$

$$\dot{q} = v\left(\frac{d\epsilon}{dr} - \frac{P}{\rho^2}\frac{d\rho}{dr}\right), \tag{3}$$

  plus corrections due to GR effects, changing $g_\star$, etc.

- For radiation-dominated ejecta, these can be converted into coupled ODEs for T, S, and v

- Integrate using boundary conditions of T and S at the PNS surface, and far pressure at the outer boundary (large radii)

Subsonic outflows (and high entropy) to the rescue

- Subsonic outflows are much more conducive to optimal νp-process yields
- Outflow spends more time in the $3\,\mathrm{GK} > T > 1.5\,\mathrm{GK}$ band where the νp-process operates optimally
- Also, the material remains closer to NS compared to supersonic outflows, allowing for greater exposure to $\bar{\nu}_e$ fluxes which make neutrons needed for (n, p) and (n, γ) reactions
- Triple-α enhancement still hurts the νp-process, but may not kill it completely!
- In addition, a high entropy $S \gtrsim 80$ is required to obtain good yields — corresponds to $M_{\mathrm{PNS}} \sim 1.8\,M_{\odot}$ for $R_{\mathrm{PNS}} = 19\,\mathrm{km}$

A comparison: subsonic vs supersonic outflows

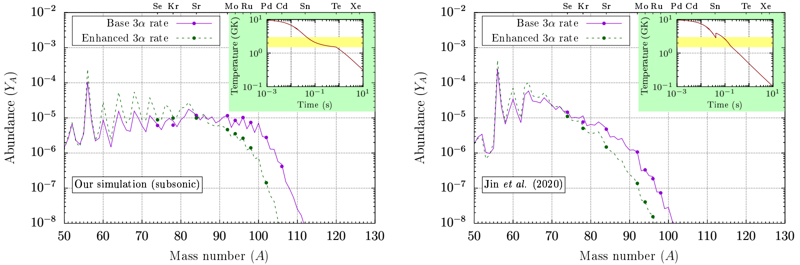
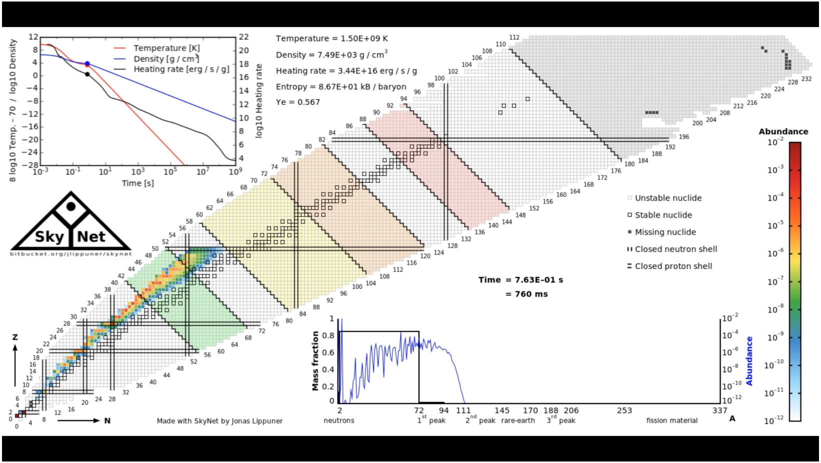


Figure: **Left:** Nucleosynthesis yields in our simulation for the base νp-process (magenta curve) and including the nominal triple-α enhancement rates (green dashed curve). p-nuclides of interest in this work are shown in solid dots.
Right: Yields obtained for parametrized outflow profile with entropy ($S = 80$) that has been used in Jin *et al.*, representing a supersonic outflow.

Nucleosynthesis calculations and inputs

- Nucleosynthesis calculations performed using open source SkyNet libraries [Lippuner and Roberts, ApJS 233, 18 (2017)]
- Triple-α enhancement was implemented using a code made available publicly by the authors of Jin *et al.* (2020)
- Neutrino luminosity taken to vary with time (exponential decay with $\tau = 3\,\mathrm{s}$) and nucleosynthesis trajectories represented by a sequence of steady-state outflow snapshots for different post-bounce times. Initial Y_e taken to be 0.6
- Self-consistent modelling of outflows using the semi-analytic framework. Post-shock densities for the far boundary condition adopted from simulations described in Sukhbold *et al.*, ApJ 821 38 (2016)

A SkyNet calculation



Different progenitor masses

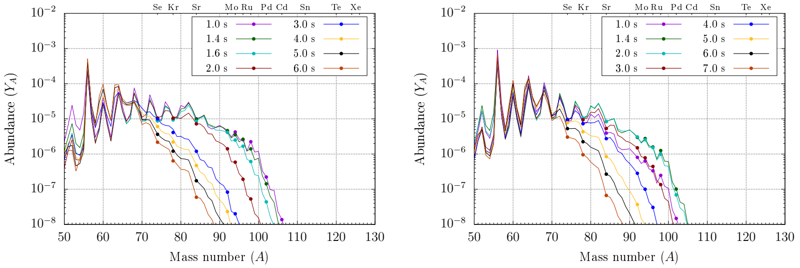


Figure: A sequence of nucleosynthesis yields computed using second-by-second outflow profile snapshots. **Left:** $13\,M_\odot$ progenitor outflow profiles. **Right:** $18\,M_\odot$ progenitor outflow profiles. In each of these cases, a PNS mass of $1.8\,M_\odot$ with a radius of $19\,\mathrm{km}$ was used in the semi-analytic outflow model.

Optimal yields reached at different times for different progenitor masses, but generally within 1–2 s when the mass outflows are still appreciable. No progenitor fine-tuning needed!

Getting the integrated yields

- For a nuclide (A, Z), we define the time-averaged abundance:

$$\langle Y_{A,Z} \rangle = \frac{\int Y_{A,Z}(t_{\text{pb}})\, \dot{M}(t_{\text{pb}})\, dt_{\text{pb}}}{\int \dot{M}(t_{\text{pb}})\, dt_{\text{pb}}}, \tag{4}$$

- The isotopic "production factor" is defined as $f_{A,Z} = \langle Y_{A,Z} \rangle / Y^{\odot}_{A,Z}$, where $Y^{\odot}_{A,Z}$ is the observed mass fraction of that isotope in the solar system (normalized so that $\sum A\, Y^{\odot}_{A,Z} = 1$ over all the nuclides)

- The "overproduction factor" is then given by $O_{A,Z} = f_{A,Z} \times (M_{\text{out}}/M_{\text{ejec}})$, where $M_{\text{out}}/M_{\text{ejec}} \sim 10^{-4}$. To explain the solar system abundance of a nuclide, one must have $O_{A,Z} \gtrsim 10$, and therefore $f_{A,Z} \gtrsim 10^5$

Integrated yields for the $13\,M_\odot$ progenitor calculation

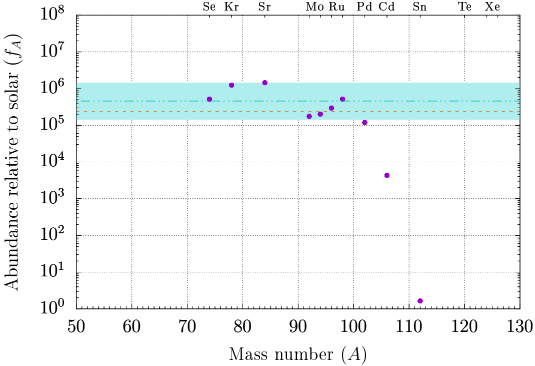
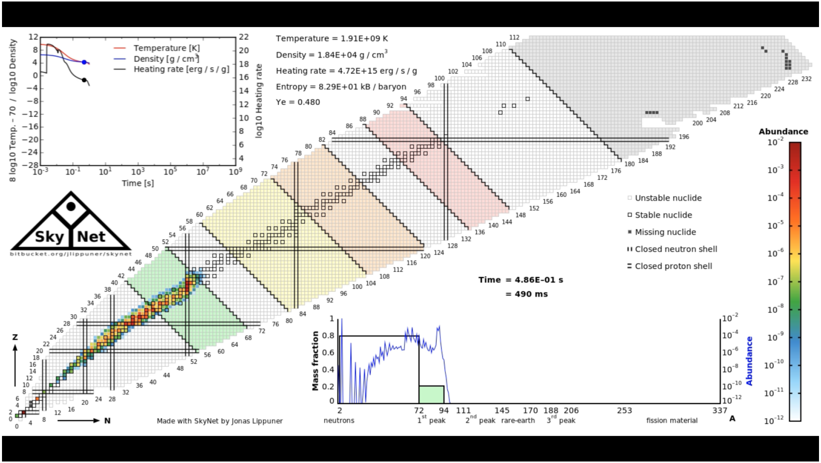


Figure: Integrated yields for the $13\,M_\odot$ progenitor calculation. The colored band represents a range of $f_{\rm max}$ to $f_{\rm max}/10$, where $f_{\rm max}$ is the highest production factor among the p-nuclides. Red dashed line represents the minimum production factor needed to account for observed solar abundances.

The α-process $(Y_e = 0.48)$ — the Niobium solution



PNS mass dependence $\implies$ variability

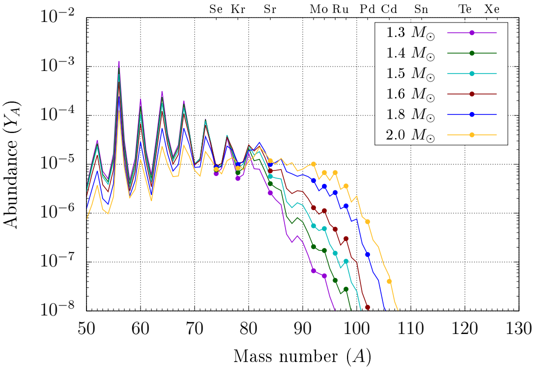


Figure: A comparison of nucleosynthesis yields for self-consistently modeled outflow profiles with different protoneutron star masses, each with radius $R_{\text{PNS}} = 19\,\text{km}$. Heavier PNS $\implies$ deeper gravitational potential $\implies$ higher entropy, which is more favourable for the νp process.

PNS radius dependence $\Longrightarrow$ EoS dependence

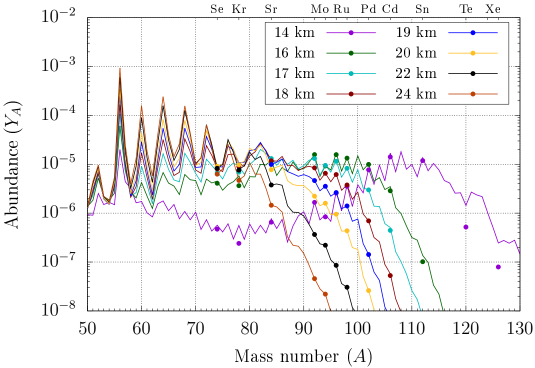


Figure: A comparison of nucleosynthesis yields for self-consistently modeled outflow profiles with different protoneutron star radii, each with mass $M_{\text{PNS}} = 1.8\,M_\odot$. More compact $\Longrightarrow$ deeper gravitational potential $\Longrightarrow$ higher entropy, which is more favourable for the νp process.

Conclusions

- νp-process appears to be alive and well! (for now at least)
- The hydrodynamics of the outflow are extremely crucial in determining νp-process outcomes
- Subsonic profiles with self-consistently modeled outflow physics can give robust νp-process yields, despite the enhanced triple-α reaction rate.
- Heavier and/or more compact protoneutron stars improve the yields considerably

Future work

- The variability of yields observed for simulations with different PNS masses offers a bridge to Galactic chemical evolution
- Dependence on PNS radius suggests possible means to get another handle on the nuclear EoS
- Dependence on Y_e motivates incorporating the effect of neutrino oscillations (see also Z. Xiong *et al.*, ApJ 900 144 (2020))
- Ultimately, all of this must be tested using nucleosyntheis calculations with 3D simulations. This framework provides guidance for such simulations.

Bonus slides

9.5 $M_\odot$ progenitor calculation

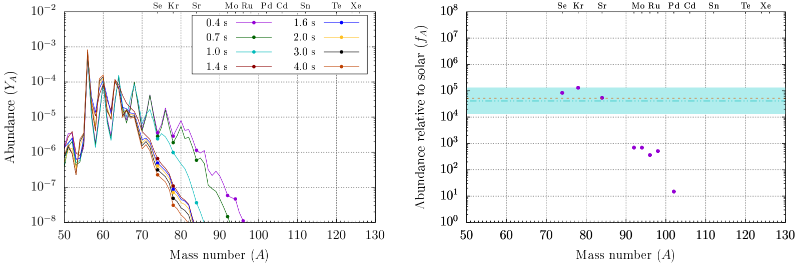


Figure: Nucleosyntheic yields for a 9.5 $M_\odot$ progenitor calculation with $M_{\mathrm{PNS}} = 1.4\,M_\odot$ and $R_{\mathrm{PNS}} = 19\,\mathrm{km}$ (low entropy) and a self-consistently modelled supersonic outflow profile. **Left:** Yields across steady-state outflow snapshots. **Right:** Integrated yields.

Outflow profiles for T vs t

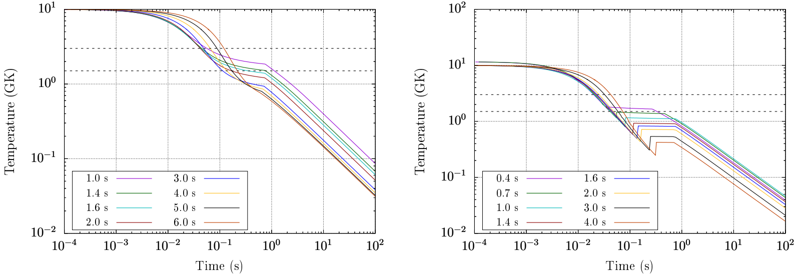


Figure: A comparison of Temperature vs time profiles for self-consistently modeled 13 $M_\odot$ (supersonic) and 9.5 $M_\odot$ (subsonic) progenitor outflows.

Variability of yields with initial Y_e

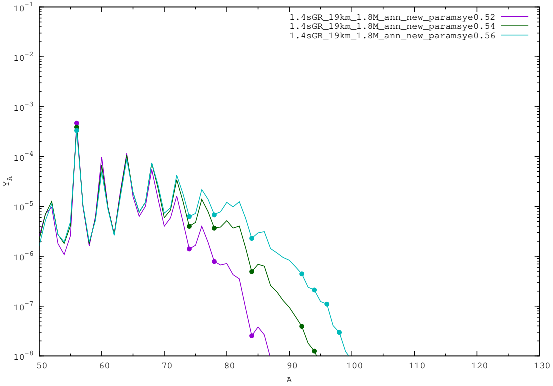


Figure: A comparison of nucleosynthesis yields for self-consistently modeled outflow profiles with different initial Y_e values.