Neutrino-driven winds and nucleosynthesis of heavy elements

Almudena Arcones[1, 2]

[1]Department of Physics, University of Basel, Klingelbergstraße 82, 4056, Switzerland
[2]Feodor Lynen Fellow, Alexander von Humboldt Foundation

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Heavy r-process elements ($Z > 56$) cannot be synthesized in the neutrino-driven winds because their entropy is too low and ejected matter is proton-rich. Neutrinos play thus a key role in determining the neutron or proton richness of the wind. We have shown that the lighter heavy elements (e.g., Sr, Y, Zr) are produced in neutron- and proton-rich winds and could explain the abundance observed in some very old halo stars.

1 Introduction

The astrophysical site where half of the heavy elements are produced by the r-process (rapid neutron capture compared to beta decay) remains unknown. The necessary neutron-rich conditions point to violent events like core-collapse supernovae and neutron star mergers (see [1] for a review). Core-collapse supernovae and the subsequent neutrino-driven winds have attracted vast attention as candidates for the production of r-process elements because they occur early and frequently enough to account for the abundances observed in old halo stars and in the solar system [2]. The necessary conditions to produce heavy elements ($A > 130$) are identified [3] (high entropies, low electron fractions, and short expansion timescales), however these are not found in the most recent long-time supernova simulations [4, 5, 6, 7].

Most of the recent progress in understanding the origin of elements commonly associated with the r-process is due to observations of ultra metal-poor (UMP) stars (see [8] for recent review). The elemental abundances observed in the atmosphere of these very old stars come from a few nucleosynthesis events. These stars generally present a robust pattern for heavy r-process elements $56 < Z < 83$, in agreement with the expected contribution of the r-process to the solar system, but show some scatter for lighter heavy elements $Z < 47$ [8]. This suggests that at least two types of events contribute to the r-process abundances (see e.g., [9]). The process leading to elements with $A < 130$ has been called in the literature the weak r-process [10], charged-particle reaction (CPR) process [11, 12, 13], and Lighter Elemental Primary Process (LEPP) [14, 15].

2 Neutrino-driven wind simulations

Recently, we have extended our spherically symmetric study [4] to two dimensional simulations [7]. In these multidimensional explosions we have shown that the neutrino-driven wind remains spherically symmetric due to the isotropic neutrino emission from a neutron star. However, the position of the wind termination shock is angle dependent due to the anisotropic distribution of early supernova ejecta (Fig. 1).

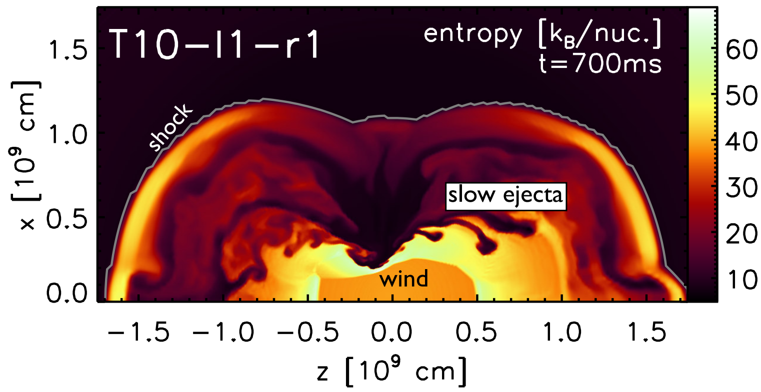

Figure 1: (color online) The neutrino-driven wind is the region of constant entropy in this two-dimensional simulation [7]. Notice the anisotropic distribution of the slow, early supernova ejecta.

In most recent hydrodynamic simulations with detailed neutrino transport, the neutrino-driven wind has relative low entropy and is proton-rich [5, 6]. The electron fraction is extremely sensitive to details of the neutrino interactions and transport around the neutrinosphere where neutrinos decouple from matter. The evolution of this region depends on the nuclear equation of state and on neutrino interactions, which are both key inputs for supernova simulations, but still very uncertain. Therefore, the electron fraction is only known approximately (see Fig. 2) and its variation can lead to different nucleosynthesis.

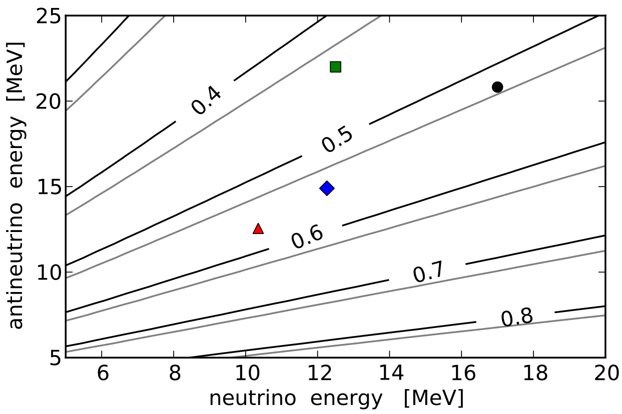

Figure 2: (color online) Contours represent the electron fraction based on the approximation of Ref. [17]. The points indicate approximately the electron neutrino and antineutrino energies for different supernova models: the green square from Ref. [18], the black circle from model M15-l1-r6 of Ref. [4], the red triangle is from a 10 $M_\odot$ progenitor of Ref. [5], and the blue diamond from Ref. [6], all at 10 s after bounce. For more details see Ref. [16].

3 Lighter heavy elements in neutrino-driven winds

The lighter heavy elements (Sr, Y, Zr) can be synthesized in neutrino-driven winds [16] as suggested in Ref. [13]. We have performed the first comparison between the LEPP abundances observed in some UMP stars and nucleosynthesis calculations based on long-time hydrodynamic simulations of core-collapse supernovae. Our results show that neutrino-driven winds can explain the observed LEPP pattern in proton- and neutron-rich conditions.

The exact calculation of the electron fraction remains a very challenging open problem [6]. As shown in Fig. 2, the antineutrino energy has decreased as the neutrino reactions and transport have been improved leading to proton-rich winds in the most recent simulations as shown by the electron fraction contours. This motivated our exploration of the impact of the electron fraction on the production of the LEPP elements. Figure 3 illustrates that the LEPP elements can be obtained for different proton- and neutron-rich conditions. Left panel in Fig. 3 shows that the LEPP pattern is reproduced in proton-rich winds. Moreover, we found that this abundance pattern is quite robust under variations of the evolution of the electron fractions. However, elements heavier than iron-group nuclei can be produced only when the neutrino fluxes are high enough to allow a successful νp-process (see, e.g., [19]). Moreover, almost only neutron-deficient isotopes are produced suggesting that proton-rich winds contribute to synthesize light p-nuclei. When the electron fraction is assumed to evolve towards neutron-rich conditions, the LEPP pattern can also be reproduced but it is very sensitive to variations of the electron fraction (right panel, Fig. 3). Moreover, in this case, there is an overproduction around $A \sim 90$. This together with the fact that most recent supernova simulations [5, 6] favor proton-rich winds could suggests that neutron-rich winds are rare events.

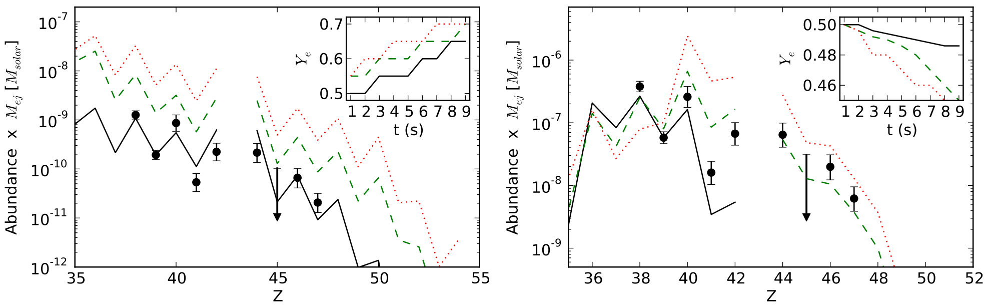

Figure 3: (color online) Elemental abundances are shown for different electron fraction evolutions and compared to observations from UMP stars (dots). See Ref. [16].

4 Conclusions

Recent long-time supernova simulations do not produce r-process elements because the wind entropy is too low and the electron fraction high, even staying proton rich during several seconds [6]. However, lighter heavy elements (e.g., Sr, Y, Zr) can be produced in proton- and neutron-rich neutrino-driven winds reproducing the abundance of UMP stars. Observation of isotopic abundances in UMP stars are very promising to constraint the neutron richness of the neutrino-driven wind and thus the evolution of the electron fraction and the neutrino properties in supernovae.

References

[1] M. Arnould, S. Goriely, and K. Takahashi. The r-process of stellar nucleosynthesis: Astrophysics and nuclear physics achievements and mysteries. *Phys. Repts.*, 450:97–213, 2007.

[2] D. Argast, M. Samland, F.-K. Thielemann, and Y.-Z. Qian. Neutron star mergers versus core-collapse supernovae as dominant r-process sites in the early Galaxy. *Astron. & Astrophys.*, 416:997–1011, March 2004.

[3] B. S. Meyer, G. J. Mathews, W. M. Howard, S. E. Woosley, and R. D. Hoffman. R-process nucleosynthesis in the high-entropy supernova bubble. *Astrophys. J.*, 399:656–664, November 1992.

[4] A. Arcones, H.-T. Janka, and L. Scheck. Nucleosynthesis-relevant conditions in neutrino-driven supernova outflows. I. Spherically symmetric hydrodynamic simulations. *Astron. & Astrophys.*, 467:1227–1248, June 2007.

[5] T. Fischer, S. C. Whitehouse, A. Mezzacappa, F.-K. Thielemann, and M. Liebendörfer. Protoneutron star evolution and the neutrino-driven wind in general relativistic neutrino radiation hydrodynamics simulations. *Astron. & Astrophys.*, 517:A80, July 2010.

[6] L. Hüdepohl, B. Müller, H.-T. Janka, A. Marek, and G. G. Raffelt. Neutrino Signal of Electron-Capture Supernovae from Core Collapse to Cooling. *Phys. Rev. Lett.*, 104(25):251101, 2010.

[7] A. Arcones and H.-T. Janka. Nucleosynthesis-relevant conditions in neutrino-driven supernova outflows. II. The reverse shock in two-dimensional simulations. *Astron. & Astrophys.*, 526:A160, February 2011.

[8] C. Sneden, J. J. Cowan, and R. Gallino. Neutron-Capture Elements in the Early Galaxy. *Ann. Rev. Astron. & Astrophys.*, 46:241–288, September 2008.

[9] Y.-Z. Qian and G. J. Wasserburg. A Model for Abundances in Metal-poor Stars. *Astrophys. J.*, 559:925–941, 2001.

[10] G. J. Wasserburg, M. Busso, and R. Gallino. Abundances of actinides and short-lived nonactinides in the interstellar medium: Diverse supernova sources for the r-processes. *Astrophys. J.*, 466:L109, August 1996.

[11] S. E. Woosley and R. D. Hoffman. The alpha-process and the r-process. *Astrophys. J.*, 395:202–239, 1992.

[12] C. Freiburghaus, J.-F. Rembges, T. Rauscher, E. Kolbe, F.-K. Thielemann, K.-L. Kratz, B. Pfeiffer, and J. J. Cowan. The Astrophysical r-Process: A Comparison of Calculations following Adiabatic Expansion with Classical Calculations Based on Neutron Densities and Temperatures. *Astrophys. J.*, 516:381–398, May 1999.

[13] Y.-Z. Qian and G. J. Wasserburg. Where, oh where has the r-process gone? *Phys. Repts.*, 442:237–268, April 2007.

[14] C. Travaglio, R. Gallino, E. Arnone, J. Cowan, F. Jordan, and C. Sneden. Galactic Evolution of Sr, Y, And Zr: A Multiplicity of Nucleosynthetic Processes. *Astrophys. J.*, 601:864–884, 2004.

[15] F. Montes, T. C. Beers, J. Cowan, T. Elliot, K. Farouqi, R. Gallino, M. Heil, K.-L. Kratz, B. Pfeiffer, M. Pignatari, and H. Schatz. Nucleosynthesis in the Early Galaxy. *Astrophys. J.*, 671:1685–1695, December 2007.

[16] A. Arcones and F. Montes. Production of Light-element Primary Process Nuclei in Neutrino-driven Winds. *Astrophys. J.*, 731:5, April 2011.

[17] Y.-Z. Qian and S. E. Woosley. Nucleosynthesis in Neutrino-driven Winds. I. The Physical Conditions. *Astrophys. J.*, 471:331–351, 1996.

[18] S. E. Woosley, J. R. Wilson, G. J. Mathews, R. D. Hoffman, and B. S. Meyer. The r-process and neutrino-heated supernova ejecta. *Astrophys. J.*, 433:229–246, September 1994.

[19] C. Fröhlich, G. Martínez-Pinedo, M. Liebendörfer, F.-K. Thielemann, E. Bravo, W. R. Hix, K. Langanke, and N. T. Zinner. Neutrino-Induced Nucleosynthesis of A>64 Nuclei: The νp Process. *Phys. Rev. Lett.*, 96(14):142502, April 2006.