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The "weak" r-process in core-collapse supernovae

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Abstract. While the origin of r-process nuclei remains a long-standing mystery, recent spectroscopic studies of extremely metal-poor stars in the Galactic halo strongly suggest that it is associated with core-collapse supernovae. In addition, recent comprehensive analysis of such stars implies the presence of the "weak" r-process that is responsible for only lighter nuclei with $A < 130$. In this study, we show that the weak r-process nuclei can be produced in the neutrino winds from a typical proto-neutron star of $1.4M_{\odot}$. This suggests that the significant fraction of weak r-process elements (Sr, Y, Zr, etc.) originate from *typical* core-collapse supernovae with the progenitor mass range of $\sim$10–$20M_{\odot}$.

Keywords. nuclear reactions, nucleosynthesis, abundances — supernovae: general

1. Introduction

The rapid neutron-capture process (r-process) accounts for the production of about half of nuclei heavier than iron, such as the bulk of noble metals (e.g., silver, platinum, and gold) and all actinides (e.g., thorium, uranium, and plutonium). In the last decade, many theoretical efforts have been dedicated to the studies related to the "neutrino wind" scenario, i.e., the r-process is expected to take place in the high-entropy, neutrino-heated ejecta from the nascent neutron star in a core-collapse supernova (i.e., Type II/Ibc supernovae, e.g., Woosley *et al.* 1994; Takahashi *et al.* 1994; Qian & Woosley 1996; Otsuki *et al.* 2000; Wanajo *et al.* 2001). All these studies involve, however, severe difficulties in obtaining requisite physical conditions for the r-process (e.g., high entropy) as well as in avoiding the overproduction of $A \approx 90$ nuclei resulting from the strong α-rich freezeout.

Despite difficulties in theoretical studies, recent comprehensive spectroscopic analyses of extremely metal-poor stars in the Galactic halo, aided with Galactic chemical evolution studies, have provided us important clues to the astrophysical origin of r-process nuclei. In particular, discoveries of extremely metal-poor, r-process-enhanced stars with remarkable agreement of their abundance patterns to the scaled solar r-process curve strongly support the idea that the r-process nuclei originate from short-lived massive stars, i.e., core-collapse supernovae (Hill *et al.* 2002; Sneden *et al.* 2003). Furthermore, the observed large star-to-star scatters of r-process elements with respect to iron suggest that the progenitors responsible for the r-process abundance production are limited to a small mass range, when combined with Galactic chemical evolution models (e.g., Ishimaru & Wanajo 1999; Ishimaru *et al.* 2004).

Besides the highly r-process-enhanced stars, there are a significant number of stars (at [Fe/H] ~ -3) that show enhancements of *only* light r-process nuclei such as Sr, Y, and Zr (Johnson & Bolte 2002). In particular, a large dispersion has been found in [Sr/Ba] at low

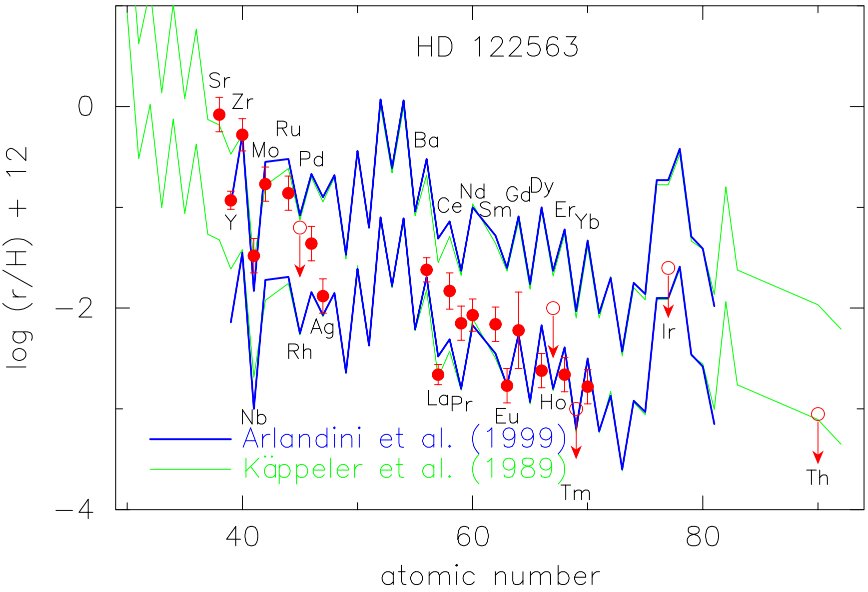

Figure 1. Observed abundances in HD 122563 (Honda *et al.* 2005). The metallicity of this star is [Fe/H] = −2.7. Detected elements are shown as filled circles with error bars. The solar r-process abundances from Arlandini *et al.* (1999, thick line) and Käppeler *et al.* (1989, thin line) are vertically scaled to match the observed Zr and Eu abundance.

metallicity, suggesting that the lighter elements such as Sr have a different origin from the "main" r-process that produces Ba and heavier elements. This may be interpreted as a result of "weak" r-processing with insufficient free neutrons at the beginning of r-process, in which only light r-process nuclei are produced. HD 122563 may be one of such stars that show abundance trends of the weak r-process (Fig. 1). The purpose of this study is to identify the astrophysical origin of the weak r-process nuclei, using the neutrino wind models developed in Wanajo *et al.* (2001, 2002, 2005).

2. Neutrino wind

After several 100 ms from the core bounce, hot convective bubbles are evacuated from the surface of a proto-neutron star, and the winds driven by neutrino heating emerge, as can be seen in some hydrodynamic simulations of "successful" supernova explosions (Woosley *et al.* 1994). Assuming the spherical symmetry, the equations of baryon, momentum, and mass-energy conservation with the Schwarzschild metric (equations (1)–(3) in Wanajo *et al.* 2001) can be solved numerically. Thus, once the neutron star mass (M), the neutrino sphere radius (R_ν), and the neutrino luminosity (L_ν) are specified along with the mass ejection rate ($\dot{M}$) as the boundary condition, the wind solution can be obtained. In this study, the neutron star mass is taken to be $1.4M_\odot$. The time evolutions of L_ν and R_ν are assumed to be $L_\nu(t) = L_{\nu 0}(t/t_0)^{-1}$ and $R_\nu(t) = (R_{\nu 0} - R_{\nu f})(t/t_0)^{-1} + R_{\nu f}$, where $t_0 = 0.2$ s, $L_{\nu 0} = 4 \times 10^{52}$ ergs s^{-1}, $R_{\nu 0} = 30$ km, and $R_{\nu f} = 10$ km, according to the hydrodynamic results of the neutrino-driven winds in Woosley *et al.* (2004). The wind trajectories are calculated for 40 constant L_ν between 0.5 and 40 ergs s^{-1} (i.e., $0.2 < t < 16$ s) with $R_\nu(L_\nu) = (R_{\nu 0} - R_{\nu f})(L_\nu/L_{\nu 0}) + R_{\nu f}$ deduced from the above equations.

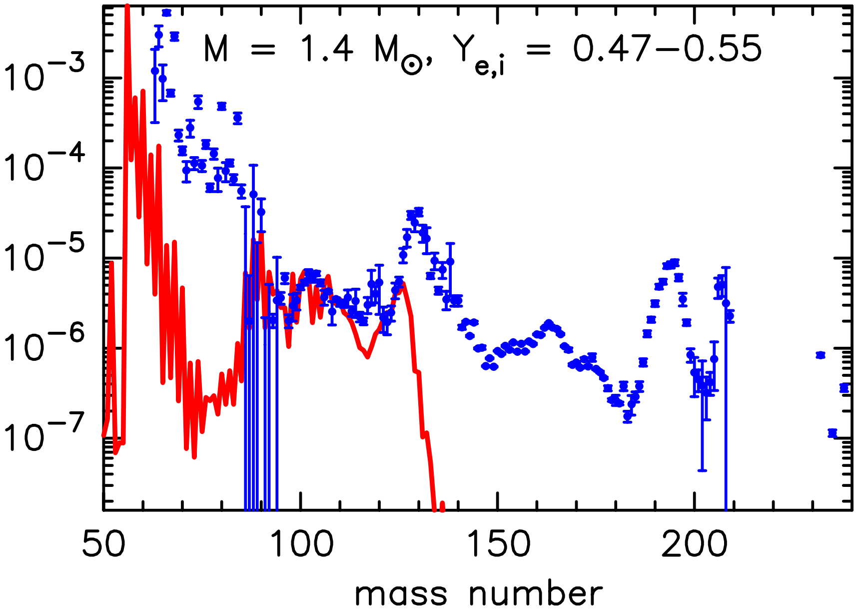

Figure 2. The final abundances as a function of mass number averaged by the ejected mass and Y_e (see text). Also denoted are the scaled solar r-process abundances (Käppeler *et al.* 1989, points). Only the nuclei between $A \approx 90$ and 120 are produced. Note that no overproduction of nuclei at $A \approx 90$ appears.

3. The r-process

The yields of r-process nuclei for each wind trajectory are obtained by application of an extensive nuclear reaction network that consists of ~5000 species along with all relevant nuclear reaction and weak rates (for the nuclear data inputs and the effects of different nuclear mass formulae on the r-process, see Wanajo *et al.* 2004). Each calculation is initiated when the temperature decreases to $T_9 = 9$ (where $T_9 \equiv T/10^9$ K). At this point the nuclear statistical equilibrium (NSE) consists mostly of free nucleons. The initial mass fractions of neutrons and protons are therefore given by $X_n = 1 - Y_e$ and $X_p = Y_e$, respectively, where Y_e is the electron fraction. In this study, Y_e at $T_9 = 9$ is assumed to be constant (Y_{e0}) for $t_0 < t \leqslant t_1$ and $Y_e(t) = (Y_{e0} - Y_{ef})(t/t_1)^{-1} + Y_{ef}$ for $t > t_1$, where $t_1 = 2$ s, $Y_{e0} = 0.47$, and $Y_{ef} = 0.35$ according to the hydrodynamic results in Woosley et al. (1994). This equation gives the initial Y_e for each wind such as $Y_e = Y_{e0}$ and $Y_e(L_\nu) = (Y_{e0} - Y_{ef})(L_\nu/L_{\nu 0})(t_1/t_0) + Y_{ef}$ for $L_\nu \geqslant 4 \times 10^{51}$ ergs s^{-1} and $L_\nu < 4 \times 10^{51}$ ergs s^{-1}, respectively.

The nucleosynthesis results are mass-averaged over the 40 wind trajectories with $\dot{M}\Delta t$ for each L_ν. Furthermore, all these nucleosynthesis calculations are repeated for the different values of Y_{e0} from 0.47 to 0.55 (nine cases). The reason is that the recent detailed hydrodynamic simulations of core-collapse supernovae with accurate neutrino transport show the electron fraction Y_e during the early phase of explosion exceeds 0.5 (Buras *et al.* 2005), which is obviously larger than that in Woosley *et al.* (1994). Finally, these mass-averaged yields are further Y_e-averaged (360 wind trajectories in total) with the Y_{e0} distribution of neutrino-processed ejecta obtained by the two-dimensional hydrodynamic simulation in Buras et al. (2005, Fig. 38). The final abundance curve is shown in Fig. 2 as a function of mass number, which is compared to the scaled solar r-process abundances. As can be seen, only lighter r-process nuclei with $A \approx 90$–120 are produced owing to "weak"

r-processing with moderate entropy ($\sim 100 N_A k$). It is noteworthy that no overproduction of the $A \approx 90$ nuclei appears in this abundance curve. This is due to the dominance of the proton-rich matter ($Y_{e0} \geqslant 0.5$) at the early phase of neutrino winds assumed in this study (Buras *et al.* 2005). In fact, the overproduction of $A \approx 90$ nuclei is still evident for $Y_{e0} < 0.49$ (non Y_e-averaged) cases. On the other hand, the overproduction disappears for $Y_{e0} \geqslant 0.49$, owing to the termination of α-process by photodisintegration at $N \approx Z \approx 28$ rather than $N \approx 50$ (Wanajo *et al.* 2002).

4. Conclusions

We showed that the neutrino winds from a *typical* proto-neutron star with $M = 1.4 M_\odot$ are likely to be the astrophysical origin of the significant fraction of "weak" r-process species ($A \approx$ 90–120), which are observed in some extremely metal-poor stars in the Galactic halo (e.g., HD 122563). This may be associated to the core-collapse supernovae with the progenitor masses of $\sim$10–$20 M_\odot$. In addition, no overproduction of $A \approx 90$ nuclei appears when considering the Y_e distribution of (mostly proton-rich) neutrino-processed ejecta obtained from a recent state-of-the-art hydrodynamic simulation. The "main" r-processing ($A > 130$) may require a more massive proto-neutron star ($\gtrsim 2.0 M_\odot$, Wanajo et al. 2001, 2002, 2005) or another astrophysical site (e.g., Wanajo *et al.* 2003).

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