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Nucleosynthesis of Mo and Ru isotopes in neutrino-driven winds

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Abstract. The solar system origin of the p-isotopes ^{92,94}Mo and ^{96,98}Ru is a long-lasting mystery. Several astrophysical scenarios failed to explain their formation. Moreover, SiC X grains show a different abundance ratio of ^{95,97}Mo than in the solar system. We have investigated if neutrino-driven winds can offer a solution to those problems.

1. Introduction

Neutrino-driven winds from nascent neutron stars are an exciting astrophysical site for the synthesis of elements between Sr-Ag. Observations of UMP stars (see e.g., [1]) have shown that those elements cannot be only produced by the r-process but rather at least one additional contribution is required [2, 3]. This astrophysical site may be the neutrino-driven wind where elements from Sr up to Ag are formed (see e.g., [4]) either by the weak r- [5] or νp-process (see e.g., [6]). It is not clear if the conditions in the wind are neutron- or proton-rich. Therefore, we investigate the nucleosynthesis for both conditions and systematically explore the impact of the wind parameters (electron fraction Y_e, entropy, expansion time scale) on the abundances (see [7]). Molybdenum and ruthenium have raised interest since several astrophysical scenarios failed to reproduce the solar system (SoS) abundance ratio of ^{92,94}Mo and ^{96,98}Ru. Besides, available data of silicon carbide grains of type X (SiC X) exhibit different isotopic ratios of ^{95,97}Mo than in the solar system. We have investigated whether the neutrino-driven wind can explain the SoS $Y(^{92}\mathrm{Mo})/Y(^{94}\mathrm{Mo})$ and the origin of $Y(^{95}\mathrm{Mo})/Y(^{97}\mathrm{Mo})$ found in SiC X.

2. Solar system abundances of ^{92,94}Mo and ^{96,98}Ru

We have performed a systematic nucleosynthesis study to identify the necessary conditions for the formation of the different Mo and Ru isotopes in neutrino-driven winds. Fig. 1 (left panel) shows the abundances of ^{92}Mo for different Y_e − entropy combinations. The color contours correspond the abundances in log scale. ^{92}Mo can be produced in neutron- ($Y_e < 0.5$) and proton-rich ($Y_e > 0.5$) conditions for a significant range of different entropies. The abundance pattern of ^{94}Mo is similar but the abundances are silghtly smaller for the same conditions. In neutron-rich winds, larger abundances of ^{92,94}Mo are obtained for smaller entropies, i.e., lower neutron-to-seed ratio. To reach ^{92,94}Mo in neutron-rich conditions the nucleosynthesis path has to move along the valley of stability. If the neutron abundance is too large the path moves

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farther away from stability and then ^{92,94}Mo are blocked due to stable ^{92,94}Zr, respectively. Therefore, it is a charged-particle process instead of a neutron capture process that synthesizes the Mo p-isotopes. In proton-rich winds, the abundances grow with increasing entropy and Y_e [8]. The νp-process forms elements via (n, p) and (p, γ) reactions which both depend on the proton abundance. Thus, with increasing proton-to-seed ratio, i.e., larger Y_e and entropy, the νp-process yields heavier elements.

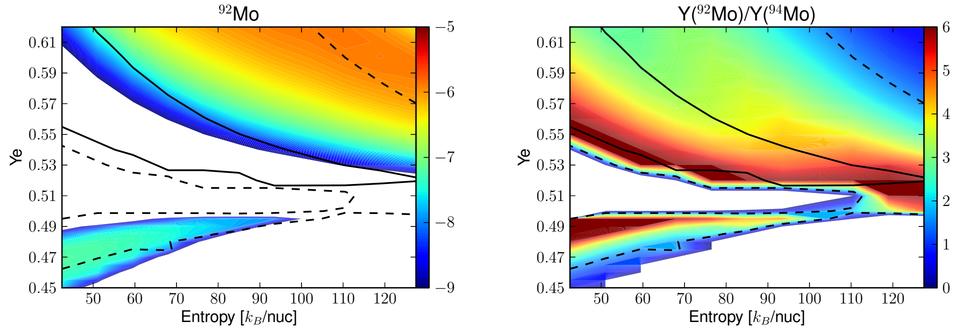

Figure 1. Left panel: Color contours show the abundances of ^{92}Mo in log scale for different Y_e and entropy. Right panel: Abundance ratio of ^{92,94}Mo for the same Y_e-entropy space. In both panels the regions where the abundance ratio of the Mo and Ru p-isotopes in the wind reaches the SoS values are indicated by dashed and solid lines, respectively.

Unlike the Mo p-isotopes, ^{96,98}Ru can only be formed in proton-rich conditions. The reason for this is that the nucleosynthesis path has to pass ^{92,94}Mo to reach the Ru p-isotopes in neutron-rich conditions, but $Y(^{92,94}\mathrm{Mo})$ are not large enough. In proton-rich conditions, the synthesis is similar to the one of ^{92,94}Mo.

To investigate if neutrino-driven winds can contribute to the SoS abundances of the Mo and Ru p-isotopes we use their SoS abundance ratios. Fig. 1 (right panel) shows the abundance ratio of ^{92,94}Mo. The dashed lines illustrate the region where the Mo p-isotope ratio in the wind is the same as in the SoS ($Y_\odot(^{92}\mathrm{Mo})/Y_\odot(^{94}\mathrm{Mo}) = 1.60$ [9]) and the solid lines mark the regions where the Ru p-isotope ratio in the wind equals the one in the SoS ($Y_\odot(^{96}\mathrm{Ru})/Y_\odot(^{98}\mathrm{Ru}) = 2.97$ [9]). The fact that solid and dashed lines do not cross implies that there is no set of wind parameters that simultaneously reproduce the solar Mo and Ru p-isotope ratios. This means that other astrophysical sites, e.g., type Ia supernovae [10], could contribute. Only with a combination of wind parameters it is possible to explain the ratios only due to the wind. A possiblity to investigate this is the production factor (see e.g., [8]). In order not to overproduce elements associated with core-collapse supernovae the production factor should be ~ 10 (see e.g., [11]). The wind fulfills the Mo p-isotope ratio in slightly neutron-rich conditions [12, 13] and $Y(^{92,94}\mathrm{Mo})$ within these conditions (Fig. 1 left panel) are sufficient. Moreover, there is an overproduction of Sr, Y, Zr due to the shell closer at $N = 50$ [14, 13]. In proton-rich winds there are two possible sites to obtain the SoS Mo p-isotope ratio. For slightly proton-rich winds [15] $Y(^{92,94}\mathrm{Mo})$ are too low. ^{92,94}Mo are produced in enough amounts for high Y_e. Here the problem is due to the Ru p-isotopes since their production factors are larger and their abundance ratio is not the solar one. Therefore, even with a combination of wind trajectories it is very challenging to explain the Mo and Ru p-isotopes in the SoS based only on neutrino-driven winds.

3. Solar system and SiC X abundances of ^{95,97}Mo

The s-, r-nuclides ^{95,97}Mo can be formed within slightly neutron-rich conditions and their abundances grow with increasing neutron-to-seed ratio, i.e., lower Y_e and higher entropy (see left panel in Fig. 2). ^{95,97}Mo are overabundant in SiC X grains in comparison to the SoS [16]. The grains indicate a mixture of SoS ^{95,97}Mo and an unknown component. Besides, SiC X grains do not exhibit an excess of ^{96,98,100}Mo that differs from a pure s- or r-process enrichment. We have investigated if neutrino-driven winds can explain the SoS abundance ratio without s-process contribution ($Y_{\odot-\mathrm{s}}(^{95}\mathrm{Mo})/Y_{\odot-\mathrm{s}}(^{97}\mathrm{Mo}) = 1.88$ [9]) that is similar to the abundance ratio found in SiC X grains ($Y_{\mathrm{SiC\ X}}(^{95}\mathrm{Mo})/Y_{\mathrm{SiC\ X}}(^{97}\mathrm{Mo}) = 1.83$ [16]). Fig. 2 (right panel) shows the abundance ratio of ^{95,97}Mo. The solid lines mark the regions for which $Y(^{95}\mathrm{Mo})/Y(^{97}\mathrm{Mo})$ in the wind is the same like in SiC X. The SoS and SiC X ratio can be obtained in the wind for a wide range of entropies and Y_e. The solid lines in Fig. 2 (left panel) show that the abundances of ^{95,97}Mo within these conditions are sufficient. Since the production factor becomes larger than 10 for those wind parameters, not all winds can have such conditions, otherwise there would be overproduction of ^{96}Zr in the SoS.

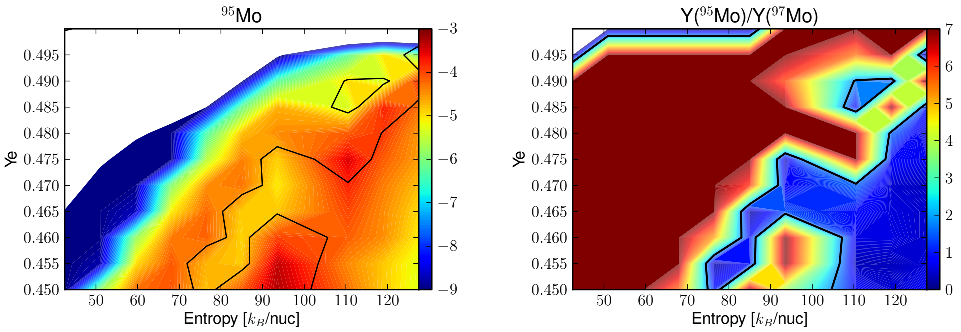

Figure 2. Left panel: Abundances of ^{95}Mo in log scale. Right panel: Abundance ratio of ^{95,97}Mo. In both panels the solid lines show the regions where $Y(^{95}\mathrm{Mo})/Y(^{97}\mathrm{Mo})$ in the wind is the same as in SiC X grains.

4. Summary

Nucleosynthesis studies like the one here combined with observations of UMP stars can help us to understand better the synthesizes of elements between Sr and Ag, and to put constraints on the wind parameters. We have shown that neutrino-driven winds can produce the SoS $Y(^{92}\mathrm{Mo})/Y(^{94}\mathrm{Mo})$ in neutron- and proton rich conditions. The SoS $Y(^{96}\mathrm{Ru})/Y(^{98}\mathrm{Ru})$ can be formed in proton-rich winds. Therefore, neutrino-driven winds may be important for the origin of SoS ^{92,94}Mo and ^{96,98}Ru but other sites e.g., type Ia supernovae [10] cannot be neglected. Besides, the wind can explain the SoS and SiC X abundances of ^{95,97}Mo.

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