

Implementing the r-process in metal-poor stars via black hole collapse and relevance to the light element enhancement

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Abstract. Recent data compilations of abundances of Strontium and Barium in Extremely Metal Poor Stars show that large fluctuations exist in the ratio of the abundances of those elements. Two models exist for explaining those fluctuations, as well as the apparent truncation of data for those elements for stars having metallicity of $[\text{Fe}/\text{H}] < -3.5$. We study the factors that place upper limits on the logarithmic ratio $[\text{Sr}/\text{Ba}]$ in the two models. A model has been developed in which the collapse of type II supernovae may produce a pronounced $[\text{Sr}/\text{Ba}]$ enhancement in single-site r-process enriched stars. This model is consistent with galactic chemical constraints of light-element enrichment in metal-poor stars.

1. Introduction

Recent studies have indicated that a population of metal-poor stars exists with abundance patterns that do not fit the universal r-process template.[1, 2, 3] A few explanations have been proposed for this. Multiple r-process sources have been proposed with contributions from each source weighted parametrically.[4] In prior work, we have addressed the issue of light-element enrichment via the so called “tr-process” [5] in which ejection of r-process material is “truncated” via fallback below the mass cut of an accretion-induced black hole. We now attempt to address the salient features of the observed $[\text{Sr}/\text{Ba}]$ distributions in metal poor stars[1] via simple hydrodynamics considerations. Specifically, we examine the Sr and Ba yields in a Population II star produced from a r-process source.

Mixing has been studied in two models. In the first model, turbulent mixing above and below the mass cut of an accretion-induced black hole is addressed and considered in a simple network calculation. In the second model, turbulence is responsible for density fluctuations in a single trajectory resulting in inhomogeneous ejection of material. In both cases, spherically symmetric hydrodynamics results[6] have been used to emulate mixing and turbulent inhomogeneities in the ejecta. While mixing between adjacent trajectories can be accomplished in a spherical model, inhomogeneous zones within a trajectory are simulated by subdivision on individual trajectories.



In addition to sharp dynamic mass cuts which limit the r-process ejecta, neutrino effects have been taken into account in calculating the effect of black hole formation on the r-process. In this regime, the neutrino emission spectra are altered as the neutrinosphere falls below the event horizon. Since the electron and anti-electron neutrinos do not have the same mean-free paths, and hence different energy spectra corresponding to different radii in the nascent neutron star, a common event horizon will result in energy spectra that differ from the usual scenario of an r-process in the environment surrounding a nascent neutron star.

In this study, we present the result of dynamic mass cuts in a collapse model. The ejection of Sr and Ba is considered, and a model which can explain the enrichment of light elements at low metallicity is presented.

2. Dynamic Collapse of r-Process Zones

To study the truncated r-process in the neutrino- driven wind, we applied the basic idea behind the study of Woosley et al.,[6] which assumed that the r-process occurred in the neutrino wind from a core collapse supernova. In that study, a succession of 40 “trajectories” (that is, thin shell wind elements), all assumed to have originated deep within the (assumed spherically symmetric) star, but having initially different conditions of density, temperature, entropy, and electron fraction, were emitted into the interstellar medium, thus contributing to the total r-process nucleosynthesis. The bubble was evolving in time, so that the conditions under which the individual trajectories were processed changed with the identity of the trajectory. We assumed that the different trajectories were emitted from the star successively, but ceased to be emitted when the collapse to the black hole occurred. Trajectories falling inside the collapse do not escape.

Truncating the r-process at higher trajectories has the effect of terminating the r-process as expected. Comparison to the low-metallicity star HD122563[2] indicates that a physical truncation of the r- process below the mass cut of an accretion- induced black hole may produce a light- element enriched r-process.

Our calculations used a network code based on *libnucnet*, a library of C codes for storing and managing nuclear reaction networks.[7] The nuclear and reaction data for the calculations were taken from the JINA reaclib database.[8] We performed calculations for trajectories 24 - 40 in the [6] hydrodynamics model. For each trajectory, reaction network calculations were performed for $T_9 < 2.5$ using initial abundances from the [6] results. Our calculations were simplified by assuming an initial abundance of massive nuclei from a single nuclear seed of mass equal to the average mass at $T_9=2.5$ and an atomic number derived from the average mass number, the Y_e , and the neutron and alpha mass fractions at $T_9=2.5$ in reference [6]. This is justified by the sharply peaked heavy-nuclide distribution near $T_9=2.5$. An adiabatic expansion was assumed for each trajectory, with entropy constant within a trajectory but varying between trajectories, again consistent with reference [6], for times at which $T_9 < 2.5$. The material expanded at constant velocity on a time scale consistent with that from prior calculations. Each calculation was continued until the abundance distribution versus mass number had frozen out.

Previous results have indicated that a truncation in the r-process in type II supernovae due to a collapse of the protoneutron star into a black hole may be responsible for an enrichment of light elements in some metal-poor halo stars produced by a single-site r-process.[5] This “tr-process” could be caused by either a dynamic collapse of material below the black hole mass cut or by a change in the neutrino luminosity resulting in an increased Y_e in the early nucleosynthesis.

We adopt a model based on prior calculations in which the Sr and Ba production in an r-process is directly related to the post-bounce time of black hole formation as shown in Figure 1. As with the initial tr-process model, we assume that the r-process is universal in post-bounce ejection time of r-processing zones in a type II supernova independent of the mass of the progenitor star. This simplification will be addressed in future work. As the goal of this work

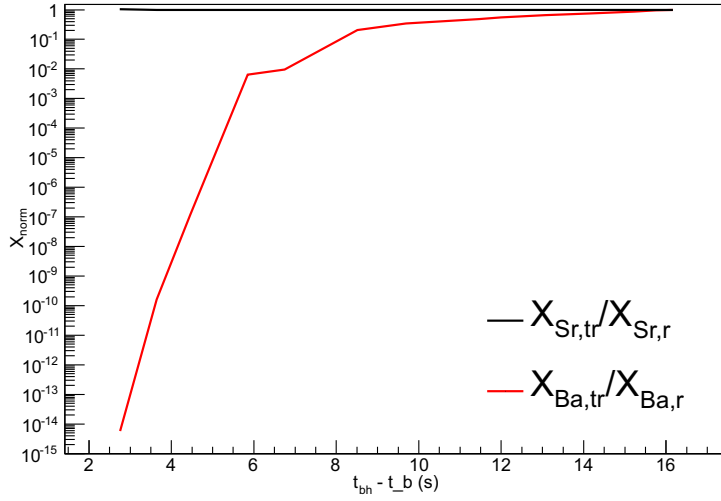


Figure 1. Sr and Ba mass fraction in an r-process site as a function of the post-bounce black hole collapse time in an r-process site.

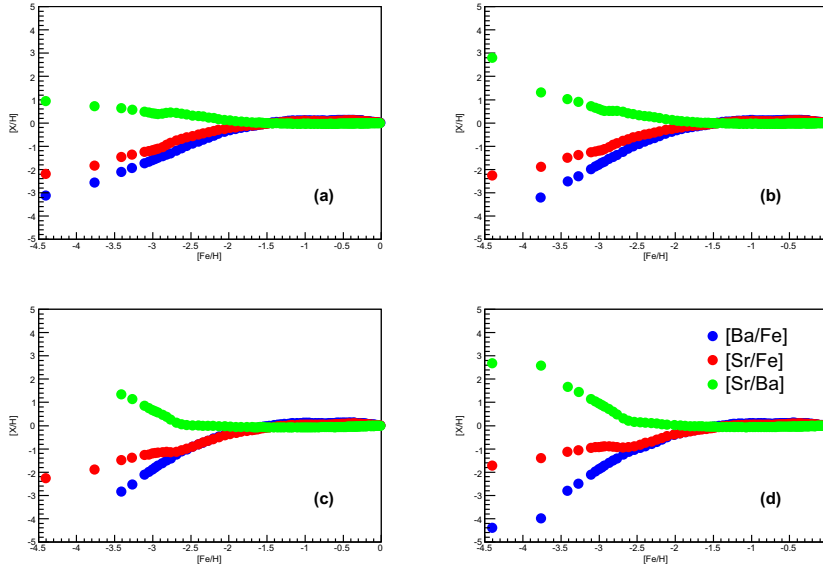


Figure 2. Results of the GCE calculation showing $[\text{Sr}/\text{Ba}]$ as a function of metallicity single-site halo stars produced in a tr-process for various assumptions of the nuclear EOS. These are (a)LS375, (b)Shenn, (c)LS220, and (d) the *ad hoc* parametrization. The assumption of an LS375 EOS closely resembles the case of no tr-process.

is to examine the sensitivity of the EOS dependence of the ejection prior to the post-bounce collapse, we maintain this assumption of universality in this simplified model. Using the model of Boyd et al.,[5] the Sr and Ba mass fractions normalized to those of a complete r-process have been determined. A value of one indicates that the resultant mass fraction in the r-process site is equal to that of a complete r-process (which produces the $A \sim 195$ peak). As Sr is produced very early on in the r-process evolution, only extremely early collapse times result in a significant

reduction of the Sr production, while the Ba abundance is built up more slowly in time; delayed black hole collapse can cut off the later ejected mass shells, which produce a more robust Ba abundance. We use this model to parametrize the Sr and Ba production as a function of collapse time in all collapse scenarios.

In order to relate the collapse time to the progenitor, results from the spherical collapse code GR1D[9] were used to study the relationship between the progenitor star's mass and metallicity and the Sr and Ba yields in massive stars. The relationship between the stellar progenitor and the compactness has been shown in previous works,[9], and the collapse time depends on a compactness in a power law relationship. This relationship has been determined for various progenitor masses and metallicities, and varies only slightly with the nuclear EOS.

Given the results from the network calculation and the collapse model, the Sr and Ba yields (normalized to a full r-process) in a tr-process can be determined as a function of progenitor mass. It is noted that these yields are minimum yields. That is, in the non-rotating spherical models employed here, the collapse times are minimum collapse times. Longer collapse times may result from asymmetric explosions, rotation, and neutrino heating.

The Sr and Ba yields as a function of progenitor mass and metallicity are placed in a galactic chemical evolution model to determine the metallicity relationship of $[Sr/Ba] = \log(Sr/Ba) - \log(Sr/Ba)_{\odot}$. [11] Results for single-site halo events have been determined. In this model, Sr and Ba yields in massive stars for a “universal” are taken from the results of references [12] and [13]. In the assumption of a single-site tr-process star, the Sr and Ba yields are scaled from the yields of [12] and [13] according to the mass and metallicity of the progenitor for each EOS.

3. Results

Assuming a tr-process model resulting in a Sr and Ba production yield, the single-site $[Sr/Ba]$ values as a function of metallicity $[Fe/H]$ are shown in Figure 2. It is seen that a softer EOS results in a progressively larger $[Sr/Ba]$ at lower metallicity (corresponding to earlier times in the galactic evolution produced by more massive stars).

If this production is a result of the tr-process, then the EOS dependence of the collapse time has a direct affect on the Sr and Ba production. Since the plotted values of $[Sr/Ba]$ are maximum values, then it would appear that in this model that a very stiff EOS cannot produce the upward scatter in $[Sr/Ba]$. A softer EOS is necessary. It's also noted that the upper limit of observed $[Sr/Ba]$ values provides an observed lower limit on the softness of the EOS.

While further work is in progress to examine some of the finer details of this effect, it is fascinating to note that the effect of a truncated r-process on GCE may be directly related to the nuclear equation of state, and astronomical observations of $[Sr/Ba]$ ratios in metal-poor stars may provide an upper limit on the stiffness of the nuclear EOS.

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