Combined Nucleosynthetic Yields of Multiple First Stars

Conrad Chan\textsuperscript{1,2} and Alexander Heger\textsuperscript{1,2,3,4}

\textsuperscript{1}Monash University, School of Physics and Astronomy, Victoria 3800, Australia
\textsuperscript{2}Joint Institute for Nuclear Astrophysics, 1 Cyclotron Laboratory, National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824-1321, U.S.A.
\textsuperscript{3}University of Minnesota, School of Physics and Astronomy, Minneapolis, MN 55455, USA
\textsuperscript{4}Shanghai Jiao-Tong University, Department of Physics and Astronomy, Shanghai 200240, P. R. China

E-mail: conrad.chan@monash.edu

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Modern numerical simulations of the formation of the first stars predict that the first stars formed in multiples. In those cases, the chemical yields of multiple supernova explosions may have contributed to the formation of a next generation star. We match the chemical abundances of the oldest observed stars in the universe to a database of theoretical supernova models, to show that it is likely that the first stars formed from the ashes of two or more progenitors.

KEYWORDS: Pop III stars, nucleosynthesis, supernovae

1. Introduction

The trace amounts of heavy elements found in observed ultra metal-poor stars most likely originated from the ashes of the first stars. The spectroscopically determined abundance patterns of these metal poor stars can be matched to the yields calculated from supernova models, in order to infer the properties of the first stars and their explosion mechanisms [1,2]. We have matched the patterns of two metal poor stars in our galactic halo. Since the surface layers of these stars have undergone minimal processing of heavier elements themselves [3, 4], they are ideal carriers of the abundance patterns of their progenitors. Their low abundances also makes it less likely that they would have been polluted by several independent sources from unrelated sites. We assume that the observational uncertainties as provided by spectroscopic abundance determination are accurate and find that individual models do not fit within error bars. Thus we consider the scenario that more than one progenitor contributed to each observed star, by matching the summation of multiple yields to observations, with the goal to find the best fitting combination of models.

1.1 Model database

We use a set of Pop III supernova model yields [2] calculated using the stellar hydrodynamics code KEPLER [5, 6]. This database has a fine resolution in progenitor mass, explosion energy, and mixing parametrization. Since the explosion mechanisms of core collapse supernovae are not fully understood [7], we assume that the solution space is contained within the extensive range of parameters of the model database. Comparing these yields to observations provides an approximate starting point to determining which explosions actually occur.

1.2 Modelling the combined chemical yields of multiple first stars

We consider the scenario where the entirety of the material ejected by multiple supernovae mix uniformly such that the chemical composition of the next generation of stars is represented propor-
tionally by the mass of the material ejected by each explosion, only diluted by pristine Big Bang material. In addition to being a physically motivated assumption, this also significantly removes the computational cost of determining the best-fitting ratio, for which physically reasonable solutions are not guaranteed.

2. Finding the best fit using evolutionary algorithms

Evolutionary algorithms are an optimisation method inspired by natural selection that is able to find approximate solutions, useful when a complete search for the exact solution is computationally expensive. Our implementation of the search algorithm, StarFit (available at http://starfit.org), defines a population of solutions as combinations of multiple models, and evolves these solutions through multiple generations until a sufficiently good solution is found. Similar to a genetic algorithm, we apply a crossover operator to solutions in order to combine their information, and a mutation operator in order to fully explore the solution space. At each generation, a selection process takes place to determine the solutions that survive onto the next generation. This selection is weighted towards high-quality fits, but all solutions have a likelihood of being selected in order to preserve diversity. We have tuned the parameters of the search algorithm to efficiently solve our problem. Typically, StarFit is able to find a high quality fit within five minutes on a single thread, rather than the two hours required for a full search.

3. Results and Conclusions

We find that for the most iron-poor star, SM0313-6708 [8], the yield from a 60 M⊙ model alone is not sufficient to explain the Li observation, for which the Li-rich 40 M⊙ yield supplements. This Li is synthesised by the ν-process in the 40 M⊙ star which has a more compact H-rich envelope [2]. We also find a small improvement for other elements, which is important given the small uncertainties that are achieved by observations. Another case that demonstrates the benefit of binary star matching is the iron-poor star HE1327-2327 [9], where the CNO-rich yield of a 75 M⊙ progenitor supplements a 10.6 M⊙ yield.

A possible explanation is the progenitors may have been wide non-interacting binary stars, which is in agreement with our current understanding that fragmentation during primordial star formation can create multiple protostars, often binaries [10–13]. The supernovae of these binaries would give a viable path to the formation of stellar-mass binary black holes in the early universe, a possibility recently confirmed by gravitational wave detections of mergers [14]. Another explanation is that the chemical contributions may originate from multiple stars in a cluster. Note, however, that our method cannot distinguish between true (gravitationally bound) binaries or multiple stars and an independent
group of these same stars, and also that combined yield scenario is just one possibility.

The apparent improvement of fit may be due to an underestimation of the error bars by observers in the measurement of spectra, or due to systematic problems in the yields from the explosion models. The results may be affected by uncertainties in stellar modelling, such as in mixing physics and entrainment, as well as uncertainties in the spectroscopically determined abundances due to NLTE and 3D effects. By considering only non-rotating stellar models, the database may not cover the necessary parameter space, or the database may be too coarsely spaced. The main caveat to our method, however, is that in general, the model database contains a wide parameterization of mixing and explosion energy values, many of which are unlikely to be realistic. Thus any statistical claims we may make on the uniqueness of our solutions are at best approximate. Nevertheless, the best matches found to the database shown here appear to be physically reasonable, and provide an insightful starting point towards constraining the explosion properties. Upcoming multi-dimensional simulations of the explosion mechanism and mixing-fallback with initial conditions motivated by these abundance matches may confirm whether or not these scenarios are indeed viable.

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