Stellar Nucleosynthesis: A timeline of Heavy Element Production

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1 Abstract

The process of heavy element production in our universe, known as the neutron capture process, occurs when heavy nuclei are assembled due to the collection of protons and neutrons. The n-capture process can be further split into two extremes- the slow process, which occurs over billions of years, and the rapid process, which occurs in some of the most brief and extreme events in our universe. By analyzing spectral lines from red giant stars in our galactic halo, we can estimate heavy element contributions from the s- and r-process. As these red giant field stars are some of the oldest stars in our galaxy, these heavy elemtent abundances can then be used to estimate the overall age of our galaxy, giving a better understanding of our evolution as a whole.

2 Introduction

The n-capture process occurs mainly in heavy elements past the iron peak, allowing for the production of rare elements that could not be constructed otherwise. The two divisions of the n-capture process further defines the production of these heavy elements.

The s-process occurs in low to intermediate mass stars that, due to their very nature, have not yet reached the end of their incredibly long lifetimes. As the star undergoes its red giant phase, slowly fizzling out over billions of years, the nuclei have time to slowly capture more and more neutrons. In addition, the long lifetime allows for beta decay to occur, allowing for special isotopes only attainable through the s-process [1].

In constraint, the r-process occurs due to some of the most violent events in our universe. In this proess, the nuclei are quickly bombarded by neutrons until the nuclei is 'dripping' with them. This process is so brief that there is no time for beta decay to occur, unlike the s-process. The most commonly accepted site for the r-process is in the core collapse of massive stars during the supernova process [2]. Although a majority of r-process heavy element production has been detected in these supernovae, new detection methods for violent events, such as gravitational waves and gamma-ray bursts, have led to new proposals for r-process sites [3]. One new proposed site for the r-process is in the decompression of the crust of neutron stars, occuring due to violent events such as a neutron star merge or the coalescence of a neutron star and a black hole [4]. These observations have been noted in recent studies, such as in the binary neutron star merger of AT 2017gfo in 2017.

The s- and r-process go hand-in-hand in creating heavy elements, with some elements gaining more from one process over the other, and some elements gaining entirely from only one process. This relationship can be used to estimate overall galactic abundances of certain heavy elements, and, in turn, give a rough estimation of our galaxy's age.

In our research, we have targeted red giant field stars within our own galaxy, utilizing the Milky Way's relationship between star metallicity and age. These red giant field stars reside in our galactic halo and are slowly cooling off over a period of billions of years. Due to their aging process and location on the main sequence track, these stars have puffed out over time, giving themselves a distended atmosphere. These factors, coupled with their isolated location on the fringe of our galaxy, make the red giant field stars perfect candidates for clear spectral data gathering. We have targeted a list of these red giant field stars using pre-existing data from the W.M. Keck Observatory, and then furthermore targeted field lines associated with three heavy elements: Barium, Europium, and Lanthanum.

All information, code, and data sets are avaliable at the GitHub repository for this project [5].

3 Data Gathering

The following stronglines were targeted for each element:

Barium: 4554 Å
Europium: 3819, 3907, 4129, 4205 Å
Lanthanum: 3949 Å

Due to data ranges and overall readability of some spectral lines, the number of stronglines varied for each of the three elements. For elements with multiple stronglines within the data range, we computed an average abundance across the computed abundances.

The abundances were computed using the astrophysics software MOOG [6], which performed a stellar line analysis on the initial dataset.

Once the data was gathered and computed for the initial dataset, we then utilized literature searches for Barium, Europium, and Lanthanum in similar red giant field stars [7, 8, 9]. This literature data was then used to supplement our existed computations, and help further define the trends within the data. As the majority of the literature data presented element abundances in $\frac{X}{Fe}$ units, with X being the respective element, we decided to use these units for our entire dataset. As our initial dataset, computed with MOOG, was in the $log\epsilon$ unit, we performed a conversion from $log\epsilon$ to $\frac{X}{Fe}$, shown in Figure 7.

4 Results

For each element, the abundances were graphed against the respective metallicity of the red giant field star, shown in Figures 1 - 3.

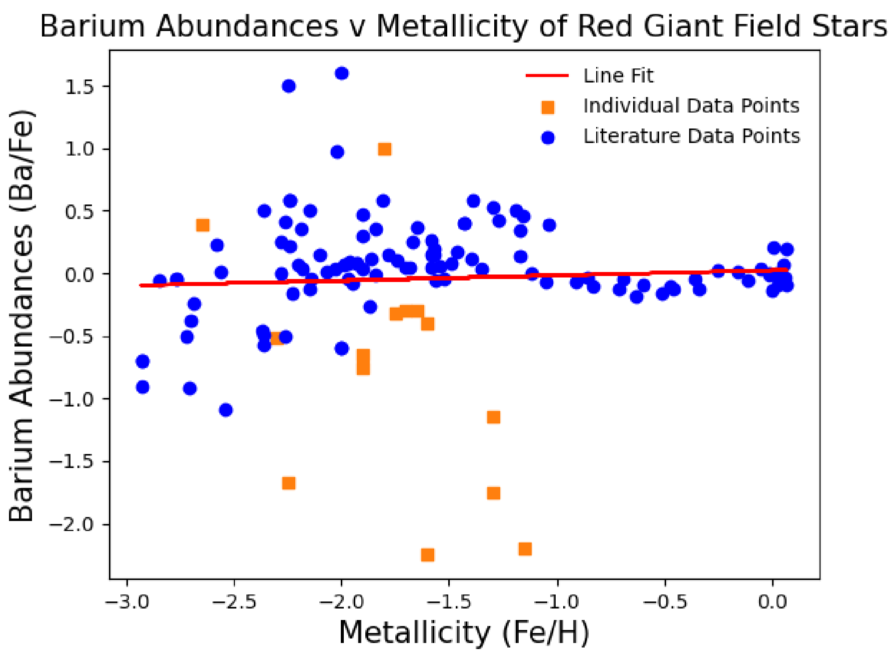

Figure 1: A graph of Barium abundances v. Metallicity of red giant field stars

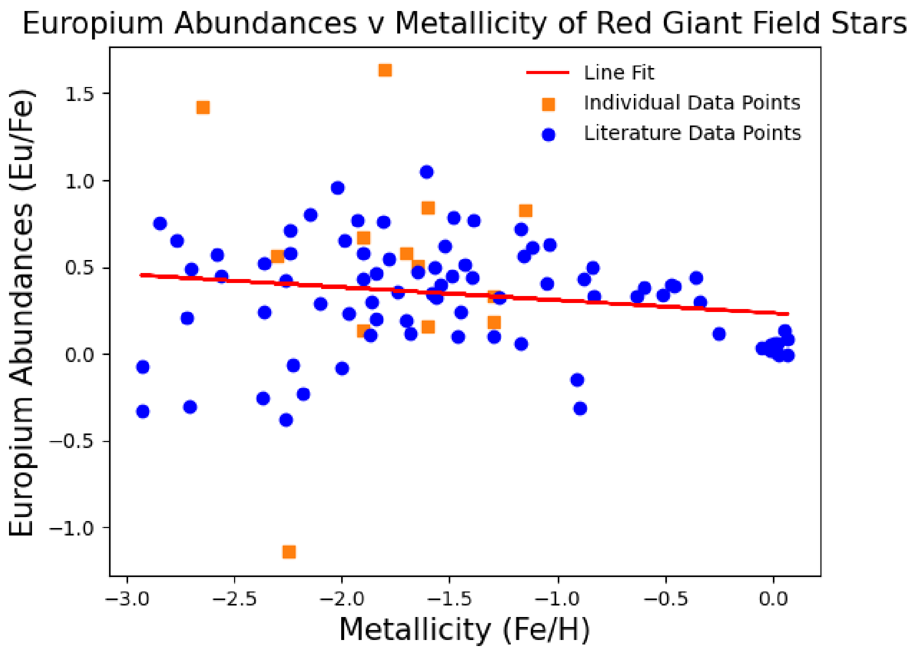

Figure 2: A graph of Europium abundances v. Metallicity of red giant field stars

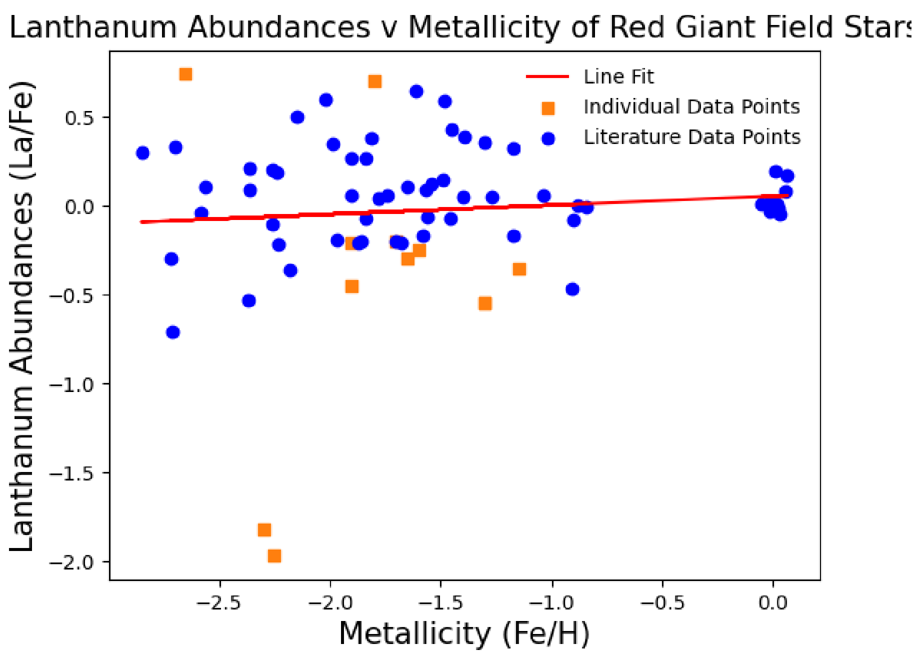

Figure 3: A graph of Lanthanum abundances v. Metallicity of red giant field stars

The resulting graphs of element abundances v star metallicity can be further analyzed to interpret the effects of the r- and s-process. As the metallicity of a star is in relation to our Sun's metallicity, a more 'negative' value representsa smaller metallicity than the Sun, whereas a more 'positive' value represents a larger metallicity. In our own galaxy, the age of stars is related to the overall metallicity, with older stars having a more negative metallicity, and younger stars having a more positive metallicity.

Europium, shown in Figure 2, clearly shows Europium's dependance on the r-process. In the younger stars, with metallicity 0.0, there is less overall mixing in the galaxy and therefore showing a more concentrated abundance of Europium. As we look towards the older stars 3.0 metalicity, we can see a slight smoothing of overall abundances due to mixing, but there is no real boost in element abundance. This proves that Europium abundances are mainly due to the r-process.

Lanthanum, shown in Figure 3, tells a similar story. In the younger stars, there is less mixing, giving a more concentrated abundance due to the r-process. In the older stars, the abundances have mixed, but the overall abundance is similar to the values in the younger stars. There is a slight boost, however, due to the s-process, which 'kicks' in the older stages of the stars' lives.

Barium, shown in Figure 1, differs from Lanthanum and Barium in that it is dominated by the s-process in the later stages of the stars' lives. The early stages are similar to Lanthanum and Barium, but there is a large jump in abundances once the s-process has had time to 'kick' in, after billions of years.

The relationships of the three heavy elements can also be expressed through comparisons, shown in Figures 4 - 6.

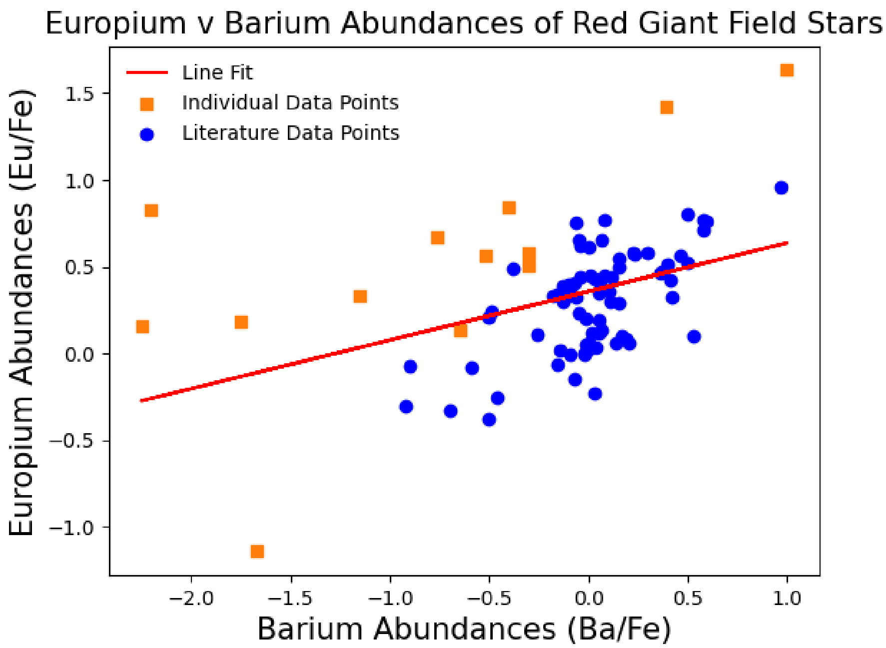

Figure 4: A graph of Barium v. Europium abundances of red giant field stars

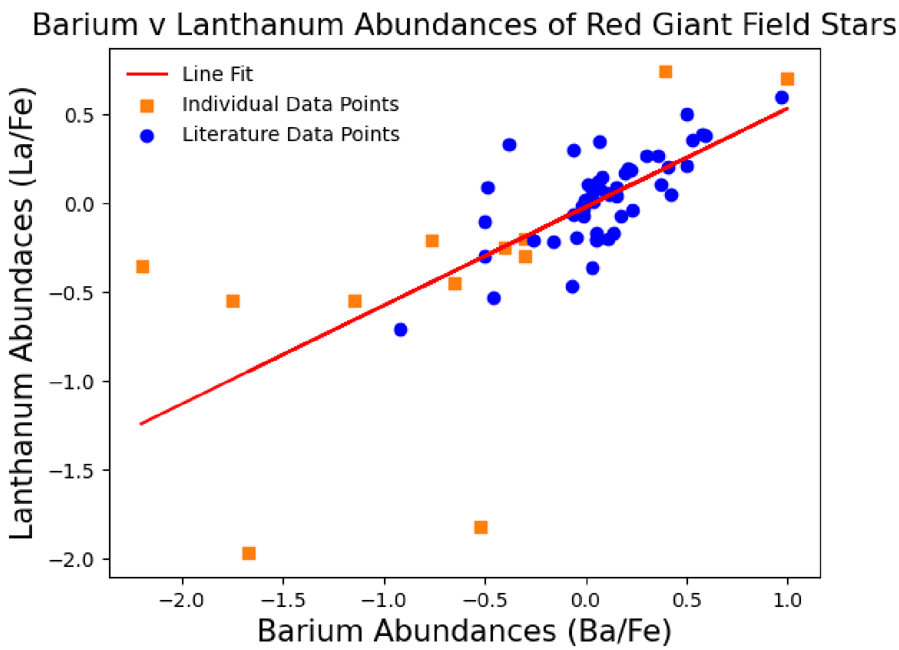

Figure 5: A graph of Barium v. Lanthanum abundances of red giant field stars

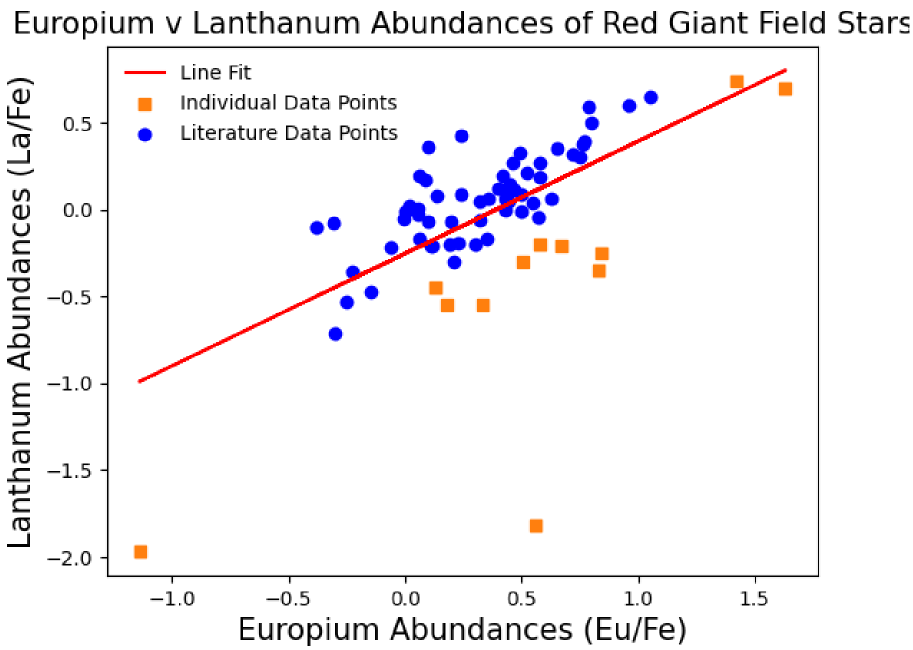

Figure 6: A graph of Europium v. Lanthanum abundances of red giant field stars

The relationship between Lanthanum and Barium, shown in Figure 5, is especially telling of the contributions from the r- and s-process. The relationship between the two elements' abundances is nearly linear, showing how both elements gain at first from the r-process, and then later from the s-process.

Europium and Barium, shown in Figure 4, is not nearly as linear, instead showing the relatively low abundance of Europium when compared to Barium. This shows the reliances of Europium on the r-process, whereas Barium gains from both the r- and s-process, causing a growing abundance over time while Europium stays stagnant. Europium and Lanthanum tells a similar story, with Lanthanum growing over time due to the r-process, whereas Europium stays similar to its starting abundances.

5 Conversions

The conversion from $log\epsilon$, used by the original MOOG dataset, to $\frac{X}{Fe}$, used by the majority of literature datasets, is shown in Figure 7.

$$\frac{X}{Fe} = log\epsilon(X) - 12 - \frac{Fe}{H} - \frac{X}{Fe}_{solar}$$

Figure 7: Equation for $log\epsilon$ to $\frac{X}{Fe}$ conversion, with X being the current element, $\frac{Fe}{H}$ being the metallicity of the respective star, and $\frac{X}{Fe}_{solar}$ being the current element solar abundance

6 Bibliography

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