Creating a Model for the Formation of Heavy Elements

Introduction

Most of the matter in space is hydrogen and helium, and it has been that way since the beginning of the universe. However, heavier elements have been formed through time. This has led to the more diverse universe of today. The main purpose of this research was to understand how these heavy elements are created by seeing the relative abundances of various heavy elements throughout time. This was done using the Stellar Abundances of Galactic Archaeology (SAGA) database.

The SAGA database has records of the relative abundances of various stars from many different scientific studies. It mainly uses bracket notation. Bracket notation compares two different elements logarithmically. For example, [Fe/H] is the following.

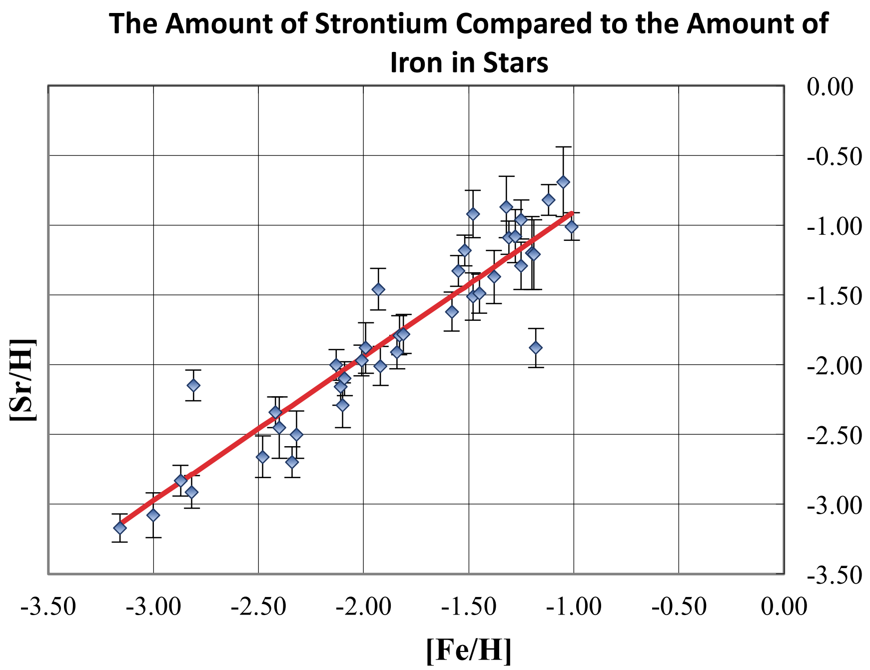
$$[Fe/H] = log_{10}(N_{Fe}/N_H)_{star} - log_{10}(N_{Fe}/N_H)_{sun} \tag{1}$$

The variable N is a count of all of the particles of that particular element observed. This notation compares other stars to our sun. Stars with a value of 1 for [Fe/H] will have ten times more iron relative to hydrogen, compared to the sun. Likewise, stars with a value of -1 will have one tenth the amount of iron relative to hydrogen. This notation can be used for other elements as well.

Because iron has increased at a relatively steady rate while hydrogen's abundance has stayed nearly constant, [Fe/H] is a good indicator of how old the star is. The data was restricted to [Fe/H] less than -1 because it limited the dataset to stars from the early universe.

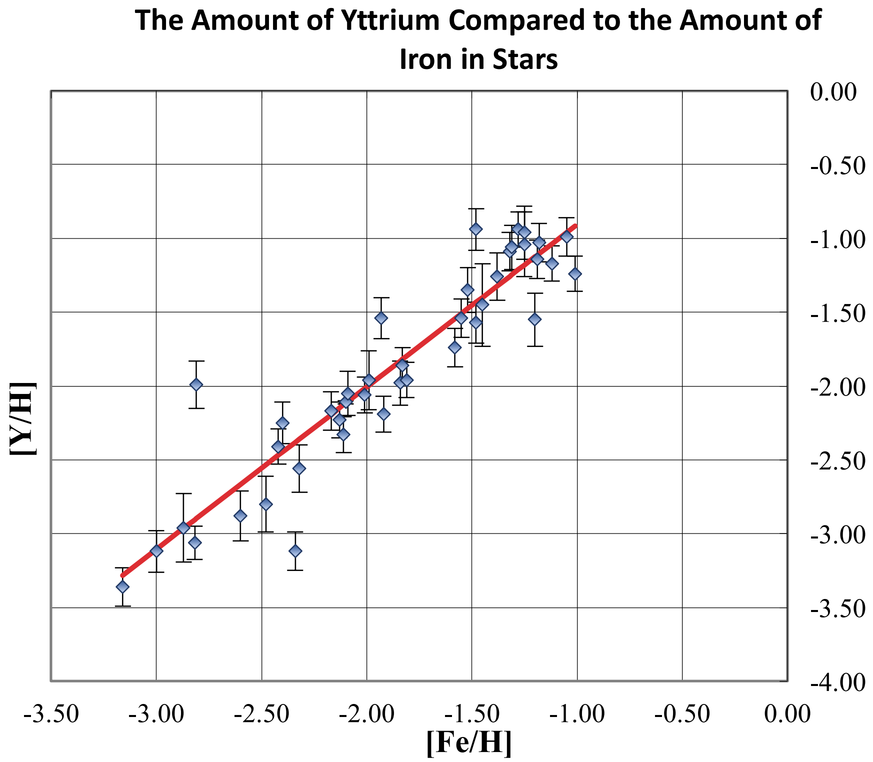
Analysis

These stars' abundances of strontium, yttrium, zirconium, palladium, and silver were compared with their abundances of iron. By plotting [X/Fe] versus [Fe/H], where X is one of the elements listed above, it was clear that these elements appeared to increase in abundance at nearly the same rate as iron.



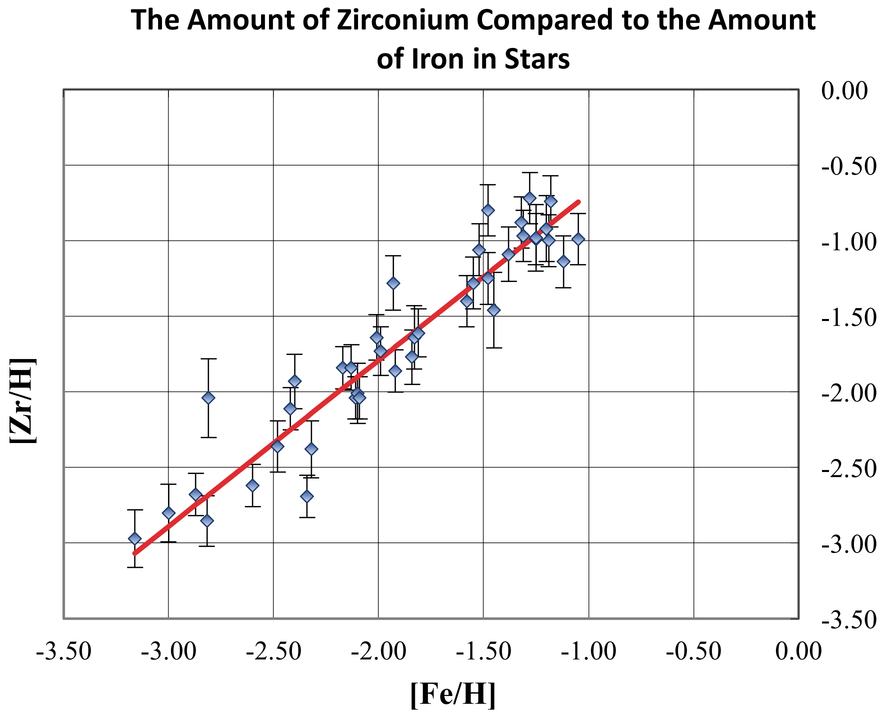
1.034x + 0.127

Figure 1- *Error in slope-* *0.035*
Error in intercept- *0.072*
Reduced chi^2 *value- 3.47*



1.101x + 0.196

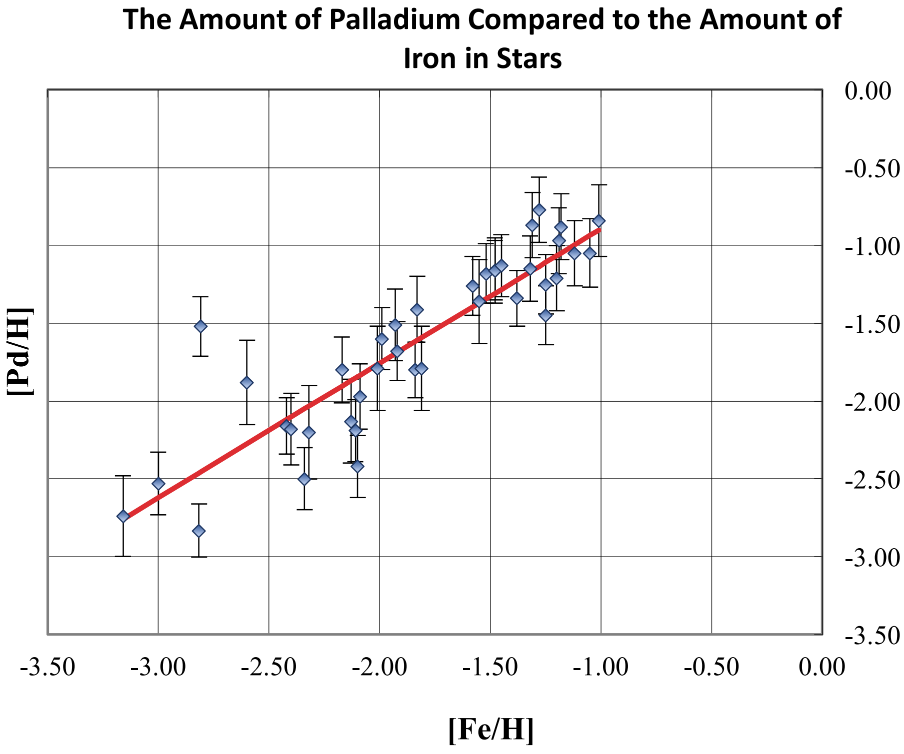
Figure 2- *Error in slope-* *0.035*
Error in intercept- *0.073*
Reduced chi^2 *value- 3.47*



The Amount of Zirconium Compared to the Amount of Iron in Stars

1.101x + 0.411

Figure 3- *Error in slope-* *0.048*
Error in intercept- *0.096*
Reduced chi^2 value- *1.60*



The Amount of Palladium Compared to the Amount of Iron in Stars

0.863x - 0.031

Figure 4- *Error in slope-* *0.059*
Error in intercept- *0.112*
Reduced chi^2 value- *1.81*

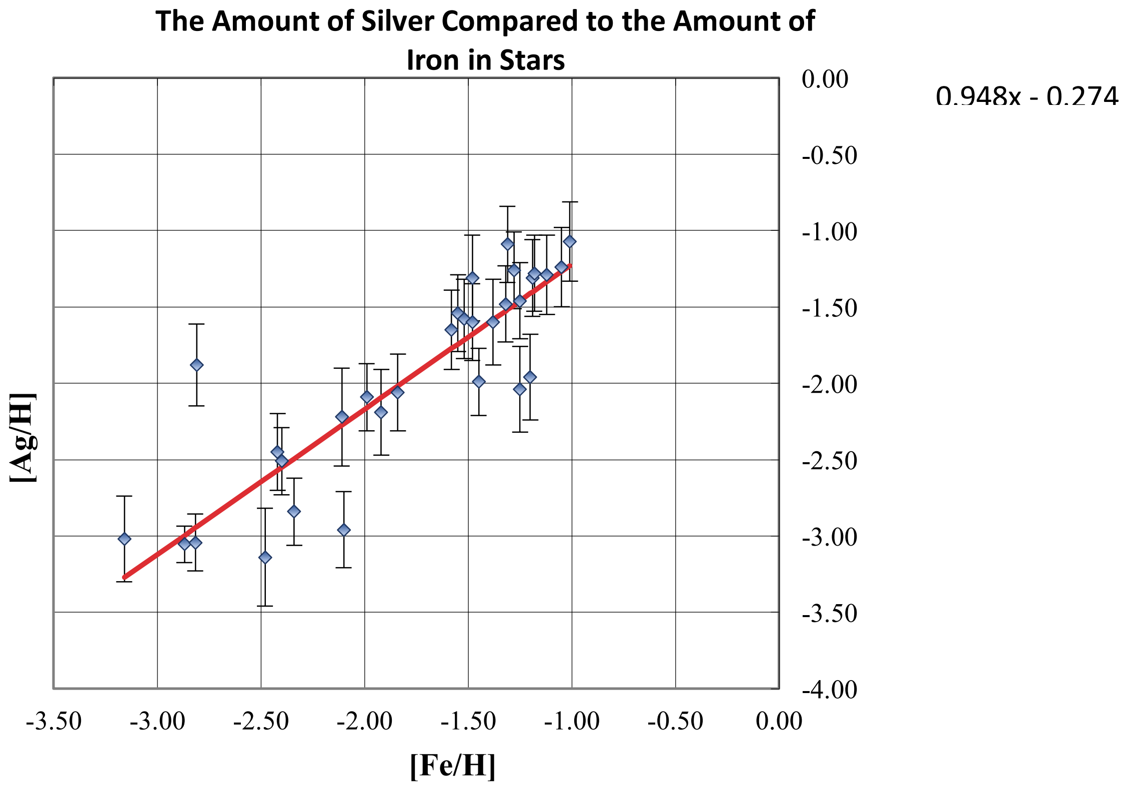


Figure 5- *Error in slope-* *0.064*
Error in intercept- *0.130*
Reduced chi^2 value- *1.66*

These five graphs show that as iron increases, other heavy elements increase as well. They also appear to increase at nearly a 1:1 ratio.

There were a few outliers from the different charts. Some of the outliers were explored further, but others suggested that the stars were not relevant to this study. In these outliers, the abundances of strontium, yttrium, and zirconium did not follow a common pattern seen amongst the majority of the stars. Normally, strontium and zirconium have similar abundances that are slightly greater than yttrium's. Many of the outliers did not follow this pattern, so they were taken out of the dataset. The reason for these stars' peculiar behavior could be explored more in other research.

Although all of the elements appeared to increase throughout time, the data did not indicate that they were created in the same way. This can be seen in Figures 6-9. If the elements were created in the exact same way, all of the points would be at (0.00, 0.00) because no star would have a unique abundance. In fact, a few outliers (stars CS31082-001 and CS22892-052) suggested there were events which affected different elements much more than others. They had much higher abundances of heavy elements compared to iron, indicating that these elements are likely made separately from iron. The simplest model that could be made has three sources for all of the heavy elements. Iron is a proxy for sources 2 and 3. Silver and palladium are proxies for source 1.

Source	Iron	Strontium/Yttrium/Zirconium	Silver/Palladium
1	No	Yes	Yes
2	Yes	Yes	No
3	Yes	No	No

Table 1

This three-source model can be derived mathematically as well. To simplify the equation, only iron, strontium, and silver will be included. Note however that silver can be replaced with palladium, and strontium can be replaced with either yttrium or zirconium. It also is important that regular parentheses are being used, not bracket notation, so the ratios are just fractions, not logarithmic.

Since strontium and silver are both made from source 1, there should be a constant rate at which they are both produced. This constant will be labelled $(Sr/Ag)_1$. The same can be done for the second source with strontium and iron, and this constant will be labelled $(Sr/Fe)_2$. The goal of the model is to predict the abundance of strontium, so this gives the following equation.

$$(Sr/H) = (Sr/Ag)_1(Ag/H) + f_{Fe}(Sr/Fe)_2(Fe/H) \tag{2}$$

$(Sr/Ag)_1$ is multiplied by (Ag/H) so that the full term represents the abundance of strontium coming from source 1. The same thing is done with $(Sr/Fe)_2$. However, (Fe/H) needs to be corrected with the term f_{Fe} because only some of the total iron is produced from source 2. This value, f_{Fe}, shows what proportion of the iron comes from source 2. Source 3 is represented by 1 - f_{Fe}. This term must be in between 0 and 1, and it changes for each star.

The whole equation can be multiplied by (H/Fe). This simplifies the equation slightly.

$$(Sr/Fe) = (Sr/Ag)_1(Ag/Fe) + f_{Fe}(Sr/Fe)_2 \tag{3}$$

Next, everything can be divided by the terms for the sun. These terms will be denoted with a subscript s.

$$\frac{(Sr/Fe)}{(Sr/Fe)_s} = \frac{(Sr/Ag)_1}{(Sr/Ag)_s}\frac{(Ag/Fe)}{(Ag/Fe)_s} + f_{Fe}\frac{(Sr/Fe)_2}{(Sr/Fe)_s} \tag{4}$$

Doing this makes it possible to convert this into bracket notation.

$$10^{[Sr/Fe]} = (10^{[Sr/Ag]_1+[Ag/Fe]} + f_{Fe}10^{[Sr/Fe]_2}) \tag{5}$$

Taking $\log_{10}$ of both sides gives the final equation.

$$[Sr/Fe] = log_{10}(10^{[Sr/Ag]_1+[Ag/Fe]} + f_{Fe}10^{[Sr/Fe]_2}) \tag{6}$$

Overall, the value of f_{Fe} should be calculated for each star. By using the database to find the values of [Sr/Fe] and [Ag/Fe], there should be values for $[Sr/Ag]_1$ and $[Sr/Fe]_2$ that require f_{Fe} to be between 0 and 1 for every star. This was done below with values of -0.43 for $[Sr/Ag]_1$ and

0.53 for $[Sr/Fe]_2$ for Figures 6-7. Figures 8-9 had values of -0.63 for $[Sr/Pd]_1$ and 0.50 for $[Sr/Fe]_2$. The y variable represents the [Sr/Fe] data collected from the database, and the x variable is the same for [Ag/Fe] or [Pd/Fe].

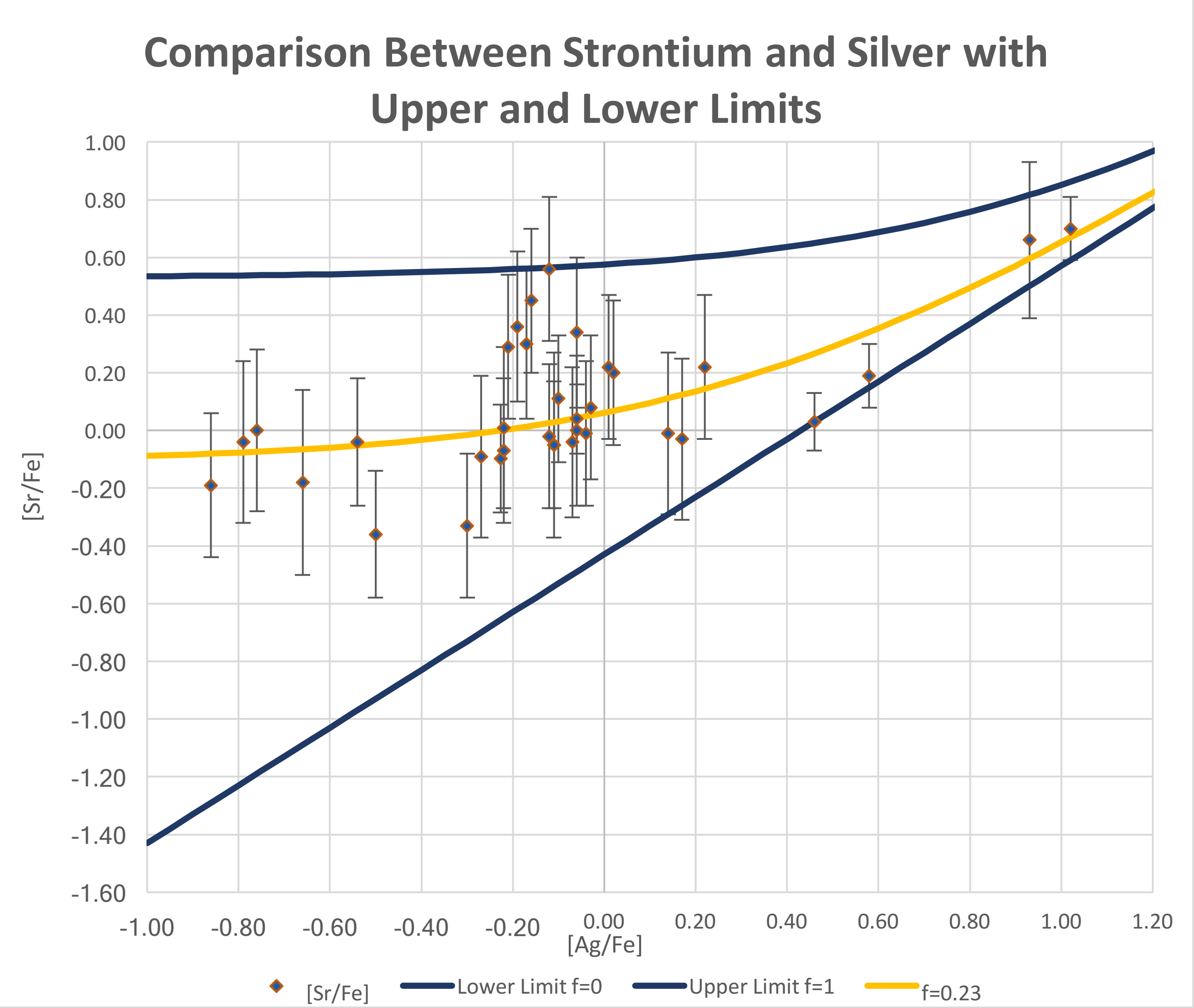


Figure 6- *Here is a graph of the data using the aforementioned model. The upper and lower limits are set for f_{Fe} = 0 and 1, respectively.*

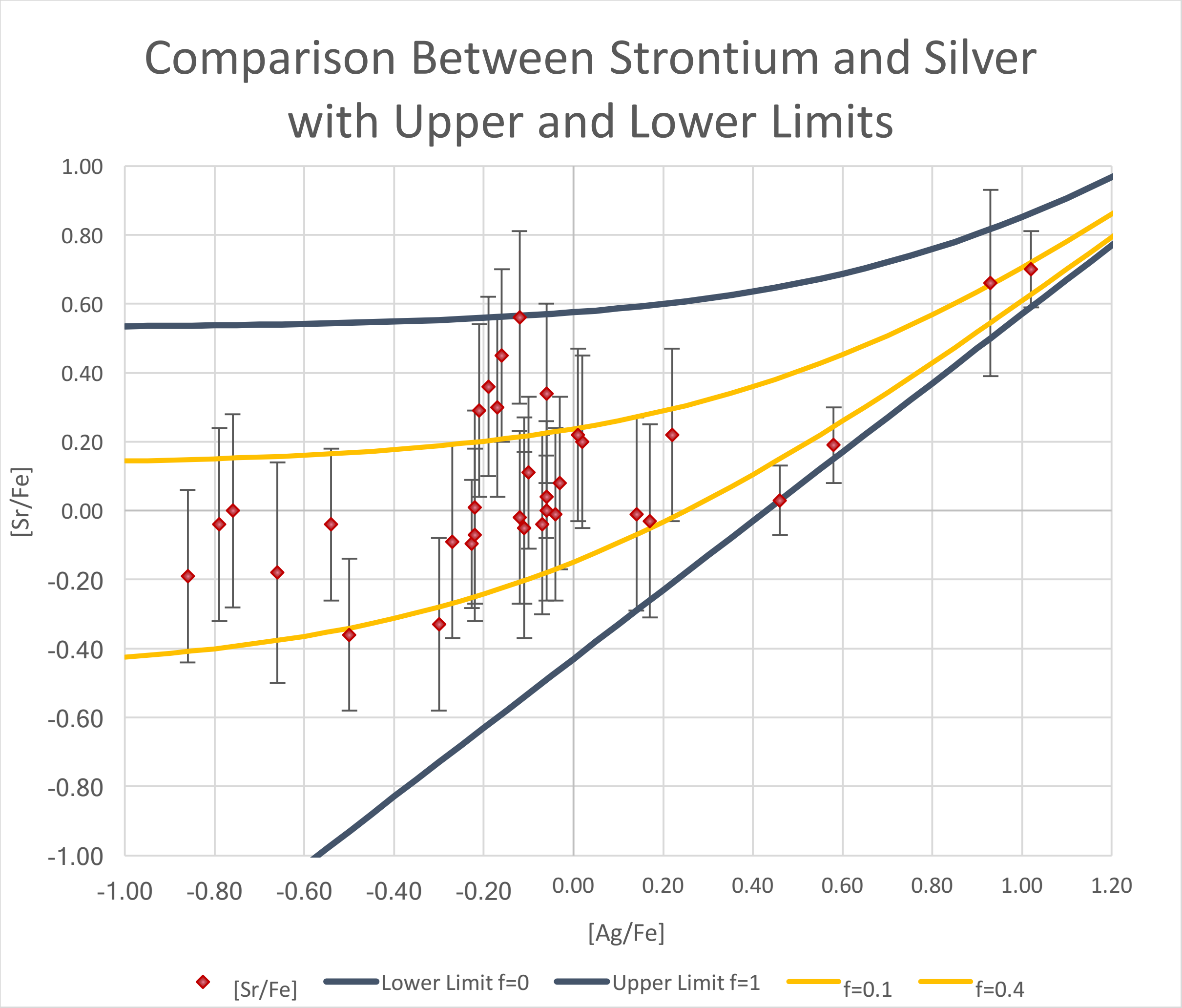


Figure 7- *This gives the same information as Figure 6. The majority of points appear to lie in between* f_{Fe}*=0.1 and* f_{Fe}*=0.4.*

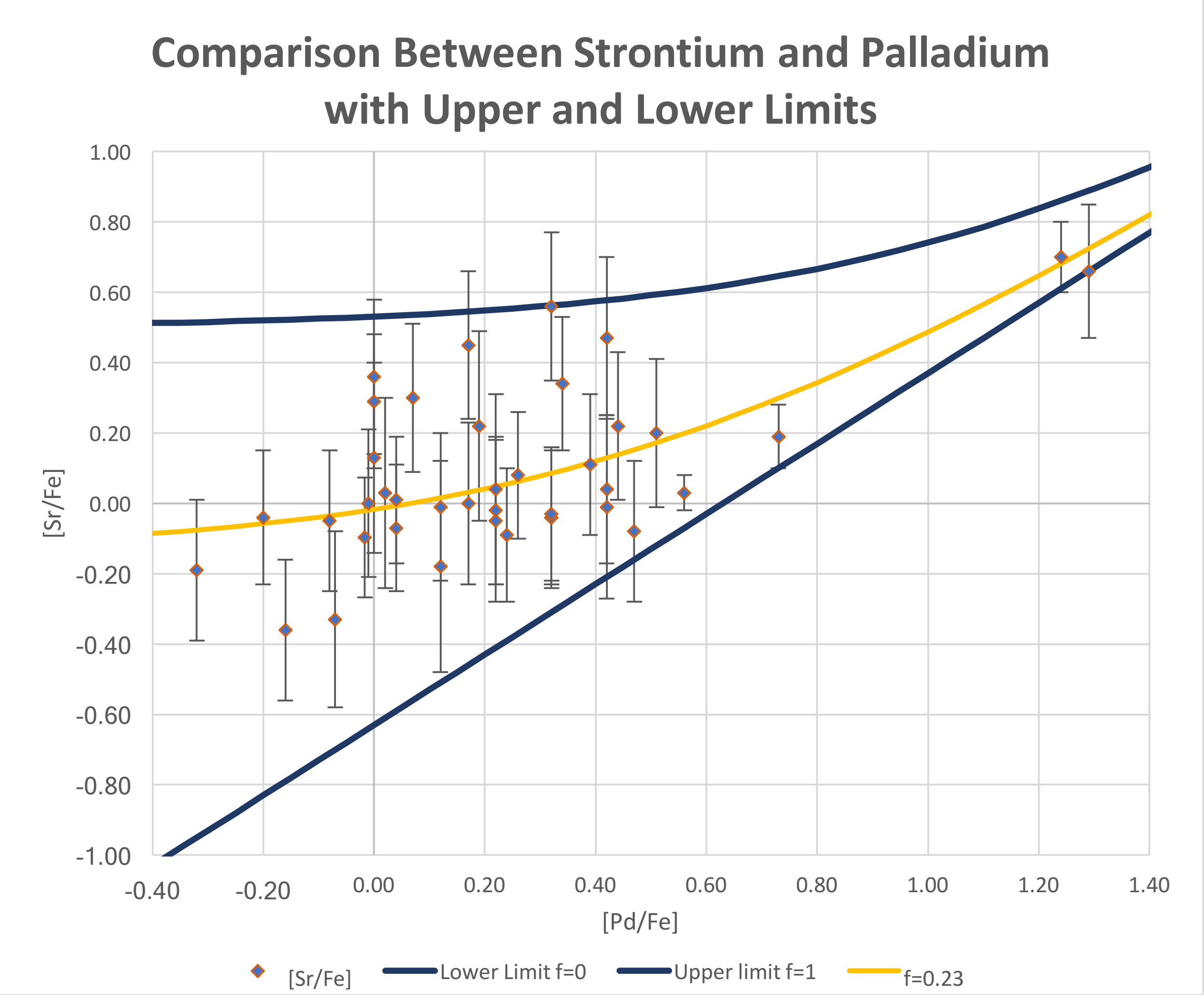


Figure 8- *This graph also uses the model above. However, silver is replaced by palladium, and the model still holds effective.*

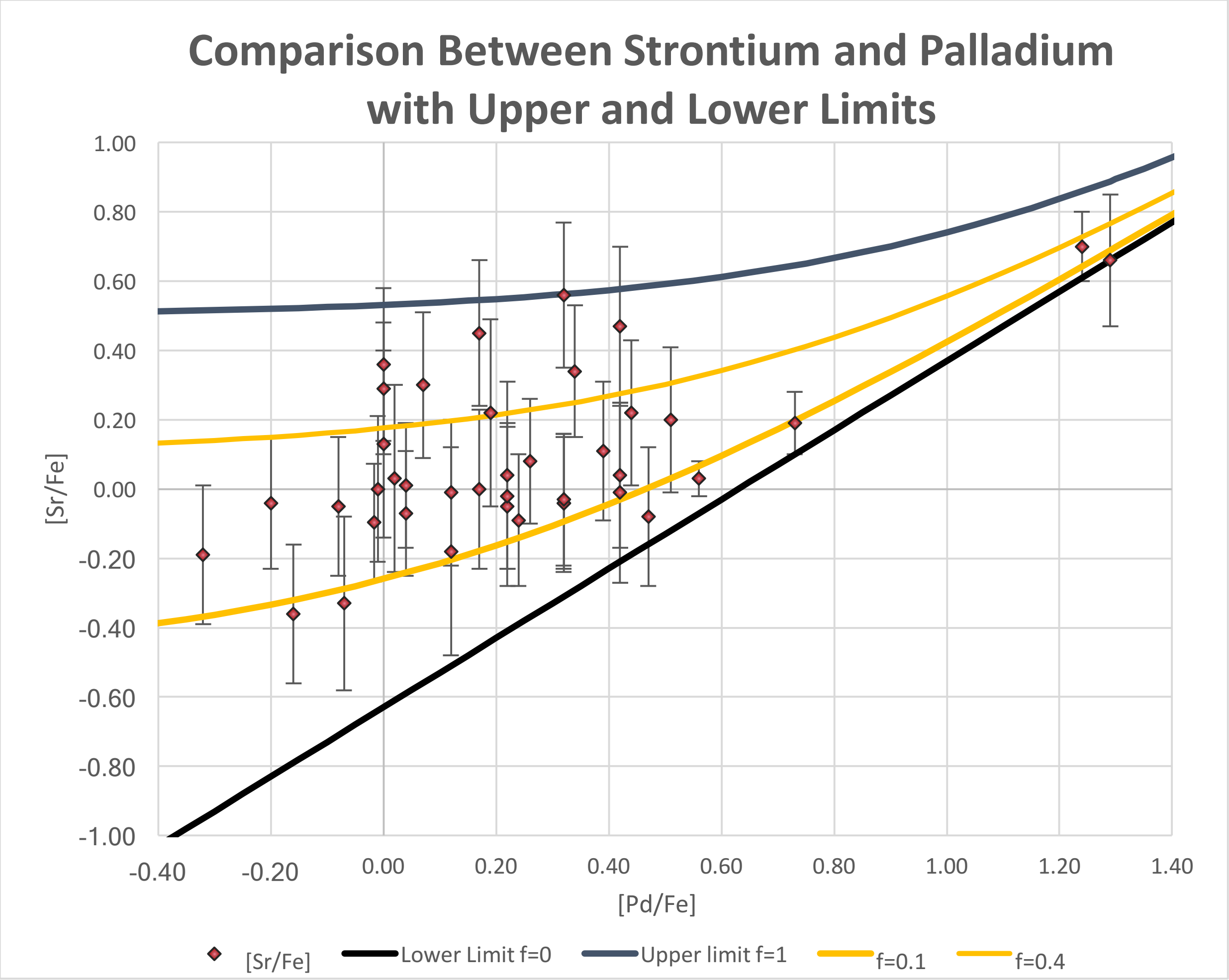


Figure 9- *This graph also shows the model with palladium, but it once again suggests that most of the stars have values of* f_{Fe} *that lie in between 0.1 and 0.4.*

Conclusion

It was determined that elements are mixed well, even in the early universe. Even though elements are well-mixed, they still are created by different sources. A model was created to account for three separate sources for heavy elements. It is reasonable because all of the points lie within the expected boundary for f_{Fe} of $0 \leq f_{Fe} \leq 1$. This model can eventually be further expanded to account for more elements.