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Uppsala University

Bachelor Thesis

Chemical signatures of the first stars

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July 1, 2017

Abstract

The first stars are something many scientists are curious about. How did they form and how did the universe look like at that time? These stars however probably died a long time ago, or are at a distance too far away from us to be observable. If these stars exploded and formed supernovae there might be stars observable today that formed from the ejecta of these supernovae. Models of nucleosynthesis in the first stars may potentially be used to infer parameters of progenitor supernovae from chemical abundances in old, metal-poor stars. This thesis aim is to find out how precise these abundances need to be to achieve a certain precision in the supernova parameters. This is done by perturbing the abundances for one element at a time in four different stars and see how the recovered supernova parameters change. The first conclusion is that it isn't necessarily the same elements that are important for determining the supernova parameters in all stars, and if there is one thing that decides which elements are important it would be the star's metallicity. The stars HE1327-2326 and HE0107-5240 metallicites are close to each other, with [Fe/H] $<$ -5.0 and [Fe/H] = -5.3 respectively, and behaved similarly, the element most important in both stars was nitrogen. The star SMSS0313-6708, [Fe/H] $<$ -7.3, had more elements that changed the parameters, the most important beeing C, O and Ca. The star CS 31028-001, [Fe/H] = -2.9, also had many elements that were important, and some of them are Na, K and Ni.

Abstract

De första stjärnorna är någonting många forskare är nyfikna på. Hur formades de och hur såg universum ut vid den tiden? Dessa stjärnor dog antagligen länge sedan, eller så är de på ett avstånd för långt bort från oss för att kunna observeras. Om dessa stjärnor exploderade och bildade supernovor är det möjligt att det finns stjärnor som går att observera som bildades ur dessa supernovor. Modeller av nukleosyntes i dessa första stjärnor kan potentiellt användas för att anta parametrar för de föregående supernovor ur den kemiska sammansättningen för gamla, metalfattiga stjärnor. Målet för denna uppsats är att ta reda på hur exakta värden som behövs på dessa kemiska sammansättningar för att nå en viss säkerhet på supernovaparametrarna. Det görs genom att ändra ämneshalten för ett ämne i taget i fyra olika stjärnor och se hur de beräknade supernovamodellsparametrarna ändras. Den första slutsatsen är att det inte nödvändigtvis är samma ämnen som är viktiga för att bestämma supernovaparametrarna i varje stjärna, och om det är en sak som bestämmer vilket ämne som är viktigt skulle det vara stjärnans metallicitet. Stjärnorna HE1327-2326 och HE0107-5240 har metalliciteter som är nära varandra, med respektive [Fe/H] < -5.0 och [Fe/H] = -5.3, och betedde sig snarlikt, så var det kväve som var det viktigaste ämnet i dessa två stjärnor. Stjärnan SMSS0313-6708, [Fe/H] < -7.3, hade fler ämnen som ändrade parametrarna och de viktigaste var C, O och Ca. Stjärnan CS 31028-001, [Fe/H] = -2.9, hade också många ämnen som var viktiga och några av dem var Na, K och Ni.

1 Background

The nature of the first stars is a question of significant importance. How did they form, live and die and enrich the enviroment with heavier elements?

A few hundred thousand years after the Big Bang the universe had cooled sufficiently so that matter recombined into atoms and the universe was largely transparent. The following epoch is called the "Dark Ages". During the Dark Ages the universe consisted essentially of only H and He, and was what is called a "metal-free" enviroment. The Dark Ages ended with the formation of the first stars, and the first stars have been given the label "Population III", or simply "Pop. III". The stars probably reionized the universe at redshifts z ~ 10 - 6 and contributed the first heavy elements to the universe thus enriching the enviroment in which galaxies started to form (Karlsson et al., 2013).

According to what is known about these stars today, it is believed that these first stars were massive and only lived for a few million years. Therefore no Pop. III stars should be left to examine in the local universe. Due to their masses they should have resulted in core-collapse supernovae, from which new stars formed (Frebel and Norris, 2015). The subsequent stars, also known as Population II (or Pop. II), believed to have been formed in gas containing material from the resulting supernova ejecta from the Pop. III stars should be able to say something about the enviroment that the Pop. III star enriched. This is one definition of Pop. II stars and the one that will be used throughout this thesis. Some of these relatively nearby stars are still likely to be visible and probe the universe at times corresponding to redshifts z > 4, so they will be possible to analyse. The Pop. II stars could give some information about the supernova from which it came, and by that also give information about the first stars (Karlsson et al., 2013). Since the Pop. III stars were the first to contribute heavier elements it is believed that the Pop. II stars ought to be metal-poor since the environment they were born in it wasn't enriched as much as if several generation of stars has enriched it.

Therefore, scientists are looking for metal-poor stars with a metallicity of [Fe/H] < -3.0. The notation [Fe/H] is a logarithmic comparison to the Sun, for example [Fe/H] = -3.0 means that the Fe/H-ratio in the observed star is 10^{-3} of the solar Fe/H-ratio. To calculate metallicity the formula is $[Fe/H] = log(\frac{N_{Fe}}{N_H}) - log(\frac{N_{Fe}}{N_H})_\odot$ (Carroll and Ostlie, 2006). Stars with low metallicity are rare, we know about 1000 observed stars that are what is called metal-poor, i.e. [Fe/H] < -3.0. The lower the metallicity, the larger the chances that the star belongs to the Pop. II generation. However a low metallicity isn't evidence that the star is old (or a Pop. II star), but a good indication that it belongs to the Pop. II stars (Karlsson et al., 2013). The Pop. II stars

contain elements produced by Pop. III stars and are tracers of the nature of the first stars and the early chemical evolution of the Galaxy.

Heger and Woosley (2010) studied the evolution and explosion of metal-free stars in the mass range 10-100 $M_{\odot}$. Simplified models are assumed where the rotation and the consequenses of rotational induced mixing are ignored and mass loss is neglected at all stages of the evolution (Heger and Woosley, 2010). Supernova models were calculated for all masses and collected in a database and fitting tool, which is avaliable online (http://starfit.org). Starfit takes a stars chemical abundances and finds the supernova model that fits best and gives the four parameters of that supernova model. The parameters are supernova mass, explosion energy, mixing and remnant mass. The chemical abundance for a star is derived from spectroscopy of the star and analysing the spectral lines (Gray, 2008). The abundance for an element i will be denoted $\epsilon_i = log(\frac{N_i}{N_H}) + 12$ where N_i is the number density of atom i and N_H the number density of hydrogen.

2 Formulation of problem

How do the parameters of an inferred supernova model change with the uncertainty of the abundances in a metal-poor star? There isn't much written about which level of precision is needed on these abundances in order to recover the parameters of the supernova at a given precision. Therefore it is difficult to say what level of precision in the measurements of the metal-poor star is needed to be able to distinguish between different metal-free supernova model parameters.

3 Aims

This project will study the necessary level of precision of the abundances so that further research about metal-poor stars can say something about the predicted supernova with better certainty. For supernova parameter P_j and abundance ϵ_i of element i, $\frac{\Delta P_j}{\Delta \epsilon_i}$ will be calculated for different stars to infer something about how precise the chemical abundance has to be in order to give a certain precision in the supernova parameters.

In particular, this study aims to determine which elements are most important in determining the parameters of the progenitor supernova as well as to see if there is a property of the stars (listed in table 1) that is particularly influental in how the supernova model parameters change.

4 Method/Material

The project will be to perturb stellar abundances of four different stars; SMSS0313-6708 (denoted as SMSS0313 in this thesis) with a metallicity of [Fe/H] < -7.3 (Nordlander et al., 2016), HE1327-2326 (denoted as HE1327 in this thesis) with a metallicity of [Fe/H] < -5.0 (Aoki et al., 2006), HE0107-5240 (denoted as HE0107 in this thesis) with a metallicity of [Fe/H] = -5.3 (Christlieb et al., 2004) and CS 31082-001 (denoted as CS 31082 in this thesis) with a metallicity of [Fe/H] = -2.9 (Hill et al., 2002). The predicted progenitor supernova model parameters will then be recovered. If ϵ_i is changed by 1 dex, the amount of that element is changed by a factor 10. In order to get a detailed view of how the parameters change each element is being changed by 0.02 dex at a time. The value will be changed, starting with the given original value of ϵ as seen in table 2 and then adding 0.02 at a time going up about one dex, and then going back to the original value and removing 0.02 for about one dex. The yielded parameter changes of the supernova, ΔP_j, will then be plotted in a graph versus $\Delta\epsilon_i$. When the plot is aquired a linear or quadratic fitting is made, depending on how the results are. The fitting will be weighted so that the data points near the original value of the element is heavier than the data points far from it. The weight, w, for each value n_i of the element is $w(n_i) = 100 - |n_i - o|$ where o is the original value of the abundance for the specific element. Depending on whether the best fit is linear or quadratic the inclination or tangent of the point at the original abundance is calculated. This to obtain $\frac{\Delta P_j}{\Delta \epsilon_i}$, a measure of how much the parameter P_j within a change in abundance ϵ_i at that point. An error estimate is then calculated by changing the weight, and by removing it and then making a fit again to see the differences. The results will be analyzed and discussed in following sections.

5 Results

For each change in abundance the derived parameter values are plotted in a graph. The graph is then labelled with a letter between a and f which describes how the data points behave. This is to be able to compare them better than just with a number, since they behave quite differently from each other. The a-type is the easiest type to calculate a value for, and doesn't give a large error. The f-type are chaotic and impossible to calculate, but the other types doesn't necessarily comes in order of how easy they are to calculate, the categorisation is more to know how the data points behave. The data points in an a is like a staircase, and the best fit is a straight line; as an example see how Na affects the remnant mass parameter for the star

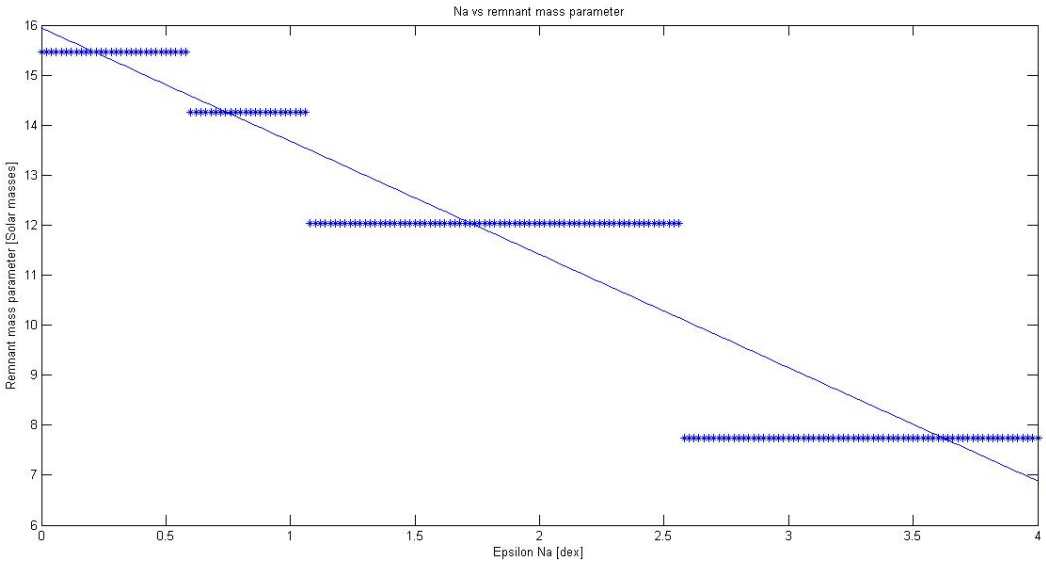

Figure 1: An example of an a-type graph, $P_{remnant}$ vs ϵ_{Na} in HE0107. A fitted curve through the data points and the tangent of the given value of abundance.

HE0107, figure 1. The letter b is similar to an a-type, the data points looks like a staircase, but in this case the curve that fits the best is a quadratic fit, which can be seen in figure 2. The letter c is for graphs that fits best with quadratic curves and the data points clearly line up fairly quadratically. An example is how Ca affects the mixing parameter in the star SMSS0313, figure 3. The d is for those graphs that are like a quadratic fit but due to for example the weight will behave differently and be difficult to analyze. Even if the weight is removed the graph will have no clear way to be described. The figure 4 is an example of where the weight of the starting point affects the best fit a lot. The e is for those that are very difficult to place in one of the other letters, although an attempt has been made, as seen in figure 5. By examing it occularly it is clear whether the parameters change alot or not at all, so a plus or minus is sometimes added after e to indicate if the supernova parameter changes a lot or not that much, respectively. For a few plots, no curve could be fitted at all, and those are marked with an f. A f-type can look much like an e-type but too difficult to do a best fit for, or be more chaotic and the chaotic type will be called $f+$. An example of a $f+$-type is Na and the mixing parameter in the star CS 31082 as seen in figure 6.

Following this the result for each star will be presented with a comment about it. It was realised that the value obtained from the graph wasn't enough to determine which element is the most important for each parameter, so therefore the classification was introduced. This however only gives an estimate of how the data points behave, and to finally determine how the

Table 1: Stellar parameters for the stars.

	T_{eff} [K]	log(g) [cgs]	Metallicity [Fe/H]	Type
SMSS0313	5125	2.3	< -7.3	Dwarf
HE1327	6180	4.5 or 3.7	-5.4	Dwarf or subgiant
HE0107	5100	2.2	-5.3	Giant
CS 31082	4825	1.5	-2.9	Giant

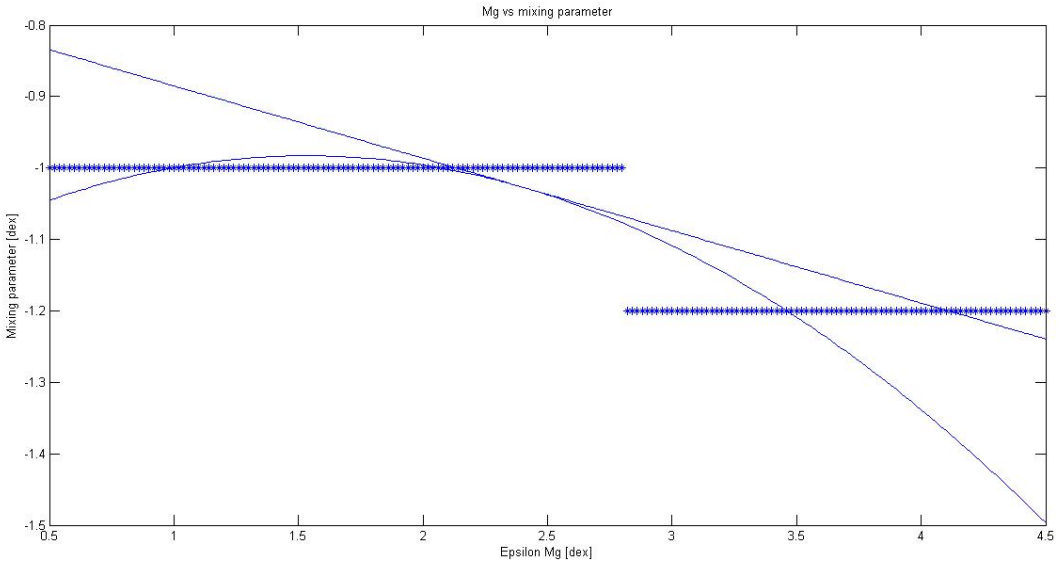

Figure 2: An example of a *b*-type graph, P_{mixing} vs ϵ_{Mg} in HE0107. A fitted curve through the data points and the tangent of the given value of abundance.

Table 2: Abundance of elements in the four stars

	SMSS0313 Nordlander et al. (2016)	HE1327 Aoki et al. (2006)	HE0107 Christlieb et al. (2004)	CS 31082 Hill et al. (2002)
Li	0.82	1.60	1.12	0.85
C	5.88	6.90	7.11	5.82
N	2.83	6.68	4.93	5.22
O	6.16	7.00	x	6.52
Na	0.34	2.92	1.86	3.70
Mg	3.77	3.57	2.41	5.04
Al	0.49	2.00	0.93	2.83
Si	1.61	x	2.55	4.89
S	x	x	7.11	x
K	x	x	x	2.87
Ca	-0.60	1.56	1.44	3.87
Sc	-2.65	x	-1.50	0.28
Ti	-2.45	-0.17	-0.62	2.37
V	-0.67	x	x	x
Cr	-0.96	x	0.65	2.43
Mn	-0.67	x	0.47	2.14
Fe	0.20	x	2.06	4.60
Co	-0.71	x	0.86	2.28
Ni	-0.98	x	0.60	3.37
Cu	-1.61	x	x	x
Zn	0.86	x	1.97	1.88
Sr	-4.33	-1.75	-2.83	x
Ba	-4.22	1.46	-2.33	x
Eu	-2.68	x	-1.99	x

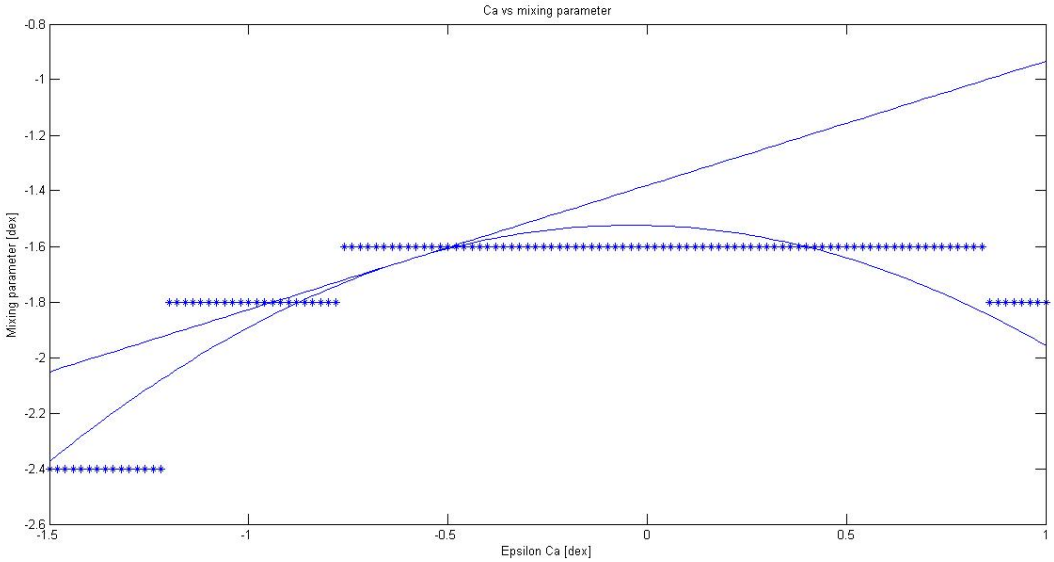

Figure 3: An example of a *c*-type graph, P_{mixing} vs ϵ_{Ca} in SMSS0313. A fitted curve through the data points and the tangent of the given value of abundance.

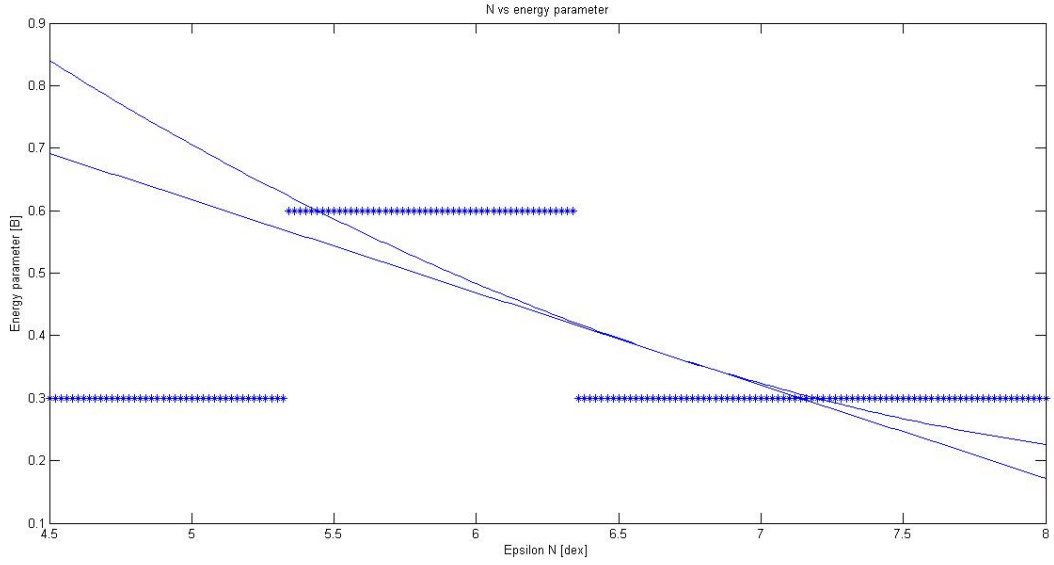

Figure 4: An example of a *d*-type graph, P_{energy} vs ϵ_N in HE1327. A fitted curve through the data points and the tangent of the given value of abundance.

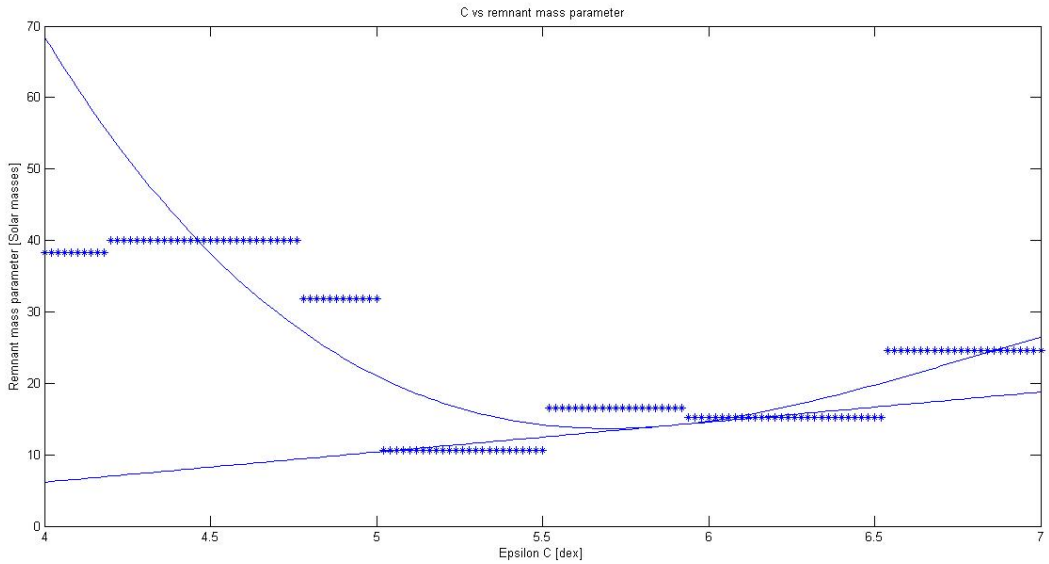

Figure 5: An example of an $e+$-type graph, $P_{remnant}$ vs ϵ_C in SMSS0313. A fitted curve through the data points and the tangent of the given value of abundance.

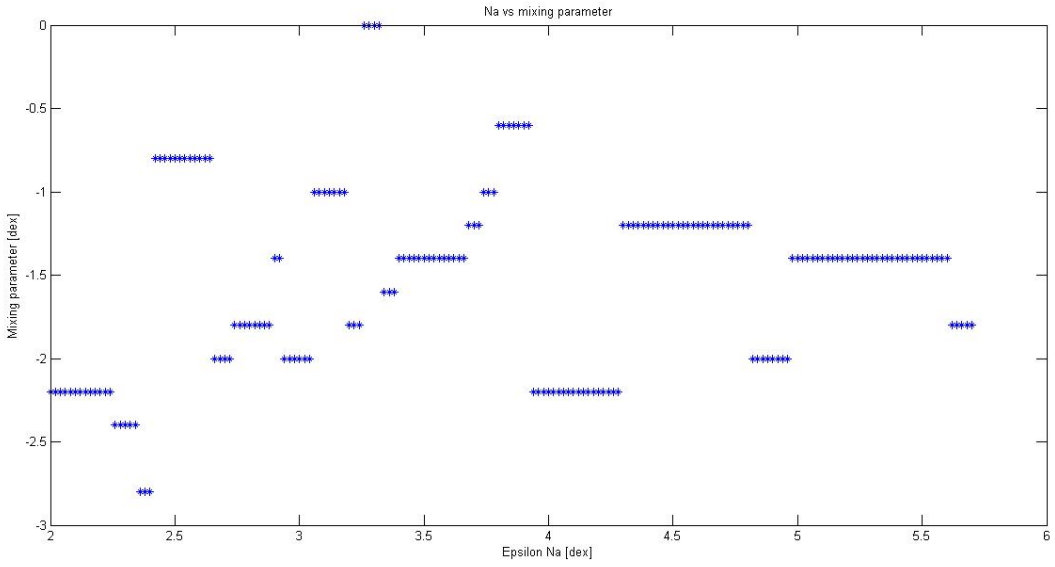

Figure 6: An example of a $f+$-type graph, P_{mixing} vs ϵ_{Na} in CS 31082. A fitted curve through the data points and the tangent of the given value of abundance.

elements change the parameter it is needed to observe the graphs. The values and classification helps to rule out the elements with no or little influence on the parameters. When stating how important an element is in determining the parameter value, it is only in comparison to the other elements and that specific parameter - not comparing its significance with the other supernova parameters. All elements which didn't affect the parameter at all have been removed from the tables. Starfit by default excludes Li, Cr and Zn so these elements will also be removed from the tables.

5.1 SMSS0313

In table 3 all obtained values for $\frac{\Delta P_j}{\Delta \epsilon_i}$ are given for each element. Apart from the excluded elements, all elements heavier than Ca have been ignored since the parameters are not sensitive to their abundances. The results which are in boxes are the elements which are most important for determining that specific parameter. When it comes to mass, it is clear that Al isn't a big factor for determing it. Nor is Na with the magnitude 0-1 $\frac{M_\odot}{dex}$, which in comparison to the other elements in this star is low. Highest $\frac{\Delta P_{mass}}{\Delta \epsilon_i}$ is Mg, with the data seen in the upper left graph in figure 7, which also has a fairly low error estimate. Oxygen lies in the same magnitude but with a higher error, upper left graph in figure 8. If we compare these data points with the eye we can see that the supernova mass changes a lot with Mg, with a big gap if we move up just a little bit in abundance. Oxygen has the same thing but moving down in abundance. Both can change the mass parameter quite a bit if the abundance isn't right, but most important is that the abundance for Mg is correct since it changes more if we move up or down in ϵ_{Mg} from the original value. The energy is a bit more difficult to analyze. It is clear that N isn't an important element, when moving one dex near the starting point the energy parameter only changes from 1.5 B (1 B = 1 Bethe = 10^{51} erg) to 1.8 B. There are two $e-$ here, both important to look at as well as high magnituded values. Ca is difficult to fit well with a curve, but doesn't change that much, so it is not one of the more important elements in determining the energy. We are left with three elements that are needed to take into consideration. C is difficult to fit a curve to, and the energy parameter changes in the proximity of the starting point. However, so does the energy parameter for both O and Mg, which has the highest value of $\frac{\Delta P_{energy}}{\Delta \epsilon_i}$, and both can be seen in the lower left graph of corresponding figures, figure 8 and 7 respectively. It is impossible to say if it is one element that changes the parameter more or less than the other two. As seen with the mixing, several elements lie within the same magnitude. As we see in the upper right graphs in figure 7 and 8, both these change the parameter a fair amount,

but in two separate ways. Mg is an e-type but O and Ca has a value in the magnitude 0.3 - 0.5 and they both behave in the same manner and must be considered as important as Mg. For the last parameter of this star, the remnant parameter, Al once again doesn't change that much and has a low value of $\frac{\Delta P_{remnant}}{\Delta \epsilon_{Al}}$. C is an $e+$-type thus having a big error, indicating that the attempt on fitting a curve is bad, see figure 5. When compared to the other elements with large values - O, Mg and Ca, it is visible that these three has the same change in remnant mass, however both Mg and Ca does change more often than O.

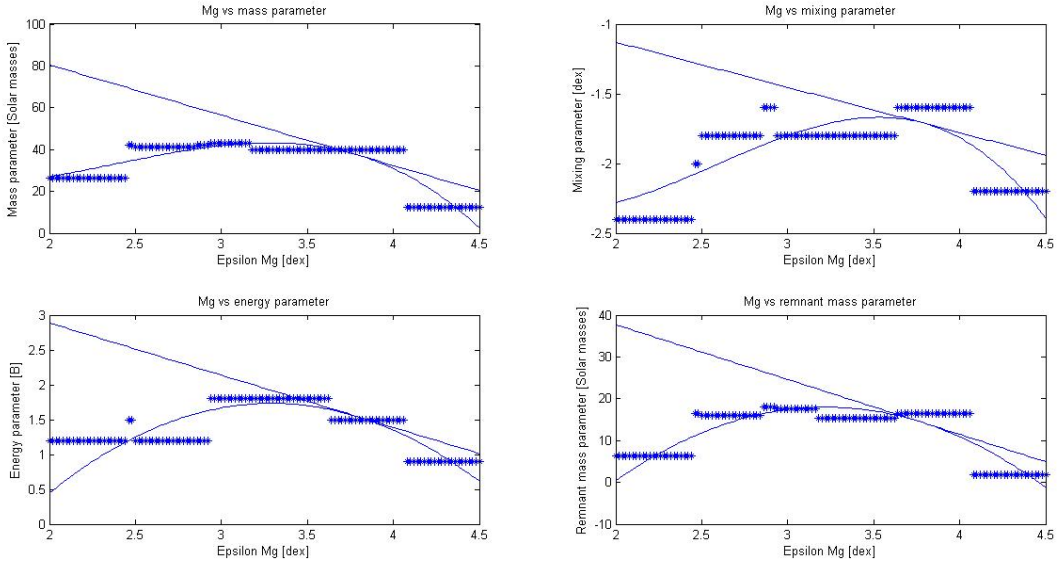

Figure 7: The data points for Mg for the star SMSS0313. A fitted curve through the data points and the tangent of the given value of abundance.

5.2 HE1327

In table 4 we see the results for HE1327. C, O and all elements heavier than and Ca has no effect on which parameter is obtained and thus only four elements remain. Starting with the mass parameter, highest values are for Na and Al, but with Na being e-type it is actually the element with highest difference in parameter for mass determination. When it comes to the energy Al has a small change in energy that doesn't appear until 1.5 dex from the starting point, that is low importance. N has the highest value and the energy changes quite close to the starting point compared to the few changes in energy for Na.

The three elements that play a roll for the mixing parameter are very near each other in magnitude, so to be able to say anything it is needed to look at the data points directly. None of the three elements really changes that much, but both Al and Mg are nearly flat, with a small

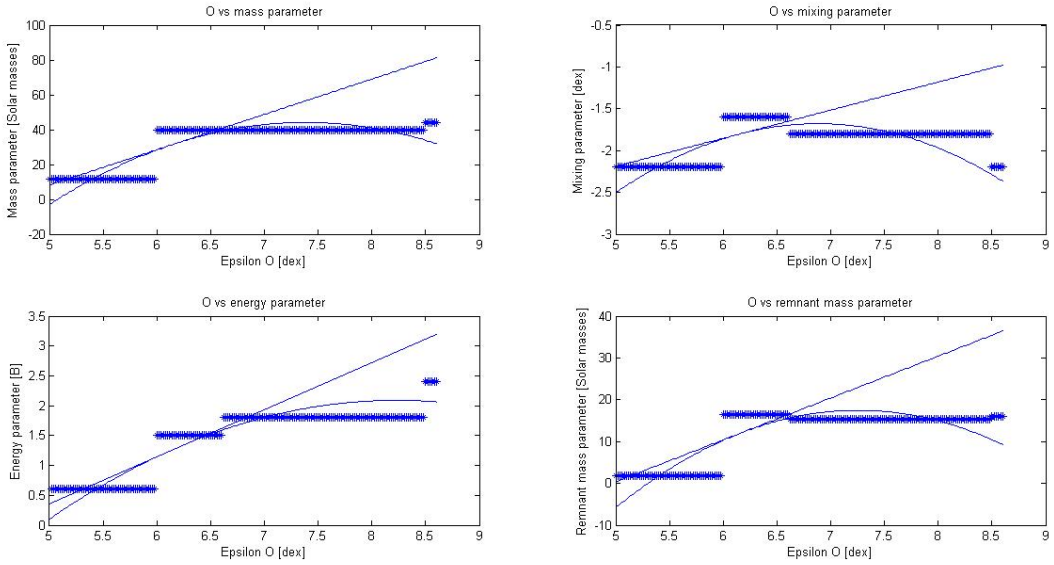

Figure 8: The data points for O for the star SMSS0313. A fitted curve through the data points and the tangent of the given value of abundance.

variance 1-1.5 dex from starting point. Na doesn't change that much either, so it is impossible to say that any of the three elements should be important in determining the mixing. For the supernova remnant parameter it is difficult to say whether it is Al or Na that are most important. Al has the highest value, but Na is *e*-type and therefore changes a lot more, but not that much when it changes. Both play an important role when determining the remnant parameter.

5.3 HE0107

C and all elements heavier than Si have been removed for HE0107. The remaining values are found in table 5. Starting with mass again Si has a low value, and according to the graph it doesn't change the parameter much. Mg has a low value but large error, and this is because it is a *d*-type. Mg is flat a few dex close to the starting point, and therefore quite unimportant for the mass parameter. Al looks quite similar to Mg, but even more difficult to do a best fit for. It is flat and the mass parameter only change by 8 $M_{\odot}$ when moving 1 dex, and thus we can claim that it doesn't play an important role. This leaves us with the two elements with high values for mass for this star, N and Na. They are of the same magnitude, with a larger error for Na than N. This error tells us that it is more difficult to do a best fit, and while examining the graphs it is clear that the mass parameter changes more in Na than N. The energy parameter is the easiest of them all, since only one element has a nonzero value. We

Table 3: Results SMSS0313, $\frac{\Delta P_j}{\Delta \epsilon_i}$. The letters after each value indicate which classification the graph is according to the description in the method. The values in boxes indicates the most important element for each parameter.

Element	Mass $[M_\odot]$	Energy [B]	Mixing [dex]	Remnant $[M_\odot]$
C	-6.84 ± 0.52^{c}	$\boxed{0.31 \pm 0.23^{e-}}$	-0.29 ± 0.02^{a}	$\boxed{4.2 \pm 11.7^{e+}}$
N	17.4 ± 3.3^{d}	0.007 ± 0.009^{d}	0.12 ± 0.01^{a}	4.41 ± 0.99^{d}
O	20.28 ± 10.68^{b}	$\boxed{0.79 \pm 0.34^{b}}$	$\boxed{0.34 \pm 0.06^{c}}$	10.01 ± 5.61^{c}
Na	0.73 ± 0.16^{b}	-0.42 ± 0.05^{b}	0.21 ± 0.03^{b}	2.15 ± 0.14^{b}
Mg	$\boxed{-24.1 \pm 0.7^{c}}$	$\boxed{-0.75 \pm 0.15^{c}}$	$\boxed{-0.32 \pm 0.006^{e}}$	$\boxed{-13.13 \pm 1.81^{c}}$
Al	0	-0.24 ± 0.06^{a}	0.16 ± 0.05^{a}	0.94 ± 0.22^{a}
Si	-9.87 ± 1.75^{b}	-0.46 ± 0.03^{b}	-0.17 ± 0.05^{d}	-4.46 ± 1.32^{d}
Ca	15.41 ± 5.91^{b}	$0.29 \pm 0.08^{e-}$	$\boxed{0.447 \pm 0.027^{c}}$	$\boxed{9.37 \pm 0.79^{c}}$

Table 4: Results HE1327, $\frac{\Delta P_i}{\Delta \epsilon_i}$. The letters after each value indicate which classification the graph is according to the description in the method. The values in boxes indicates the most important element for each parameter.

Element	Mass $[M_\odot]$	Energy [B]	Mixing [dex]	Remnant $[M_\odot]$
N	0.33 ± 0.63^{b}	$\boxed{-0.15 \pm 0.05^{d}}$	0	1.76 ± 0.8^{b}
Na	$\boxed{-1.03 \pm 3.48^{e}}$	0.04 ± 0.01^{d}	-0.05 ± 0.07^{c}	0.05 ± 1.15^{e}
Mg	1.02 ± 0.78^{c}	0	-0.08 ± 0.16^{b}	$\boxed{-0.74 \pm 0.7^{c}}$
Al	-4.3 ± 6.7^{b}	-0.03 ± 0.08^{b}	0.04 ± 0.16^{b}	$\boxed{-2.29 \pm 3.51^{b}}$

need to move almost 1.5 dex from the starting point before the energy parameter changes in the first place, so even for this element the energy parameter is quite insensitive, so for this star the energy is fairly certain independent for a large change in element abundance. Looking at the mixing parameter the values directly give the most important for determining the parameter. First we must examine how the f-type Al behaves. A quick look at the graph tells us that the parameter doesn't change that much, thus being an unimportant f-type element. This leaves us with the high valued element which is the element that changes the parameter the most, N. Al is a f-type even for the remnant parameter, so we begin by finding out if it is important or not in determining the parameter. It is a flat type that has a small role for the remnant. N has a value that is clearly higher than the rest, since the error is small for all elements. This gives us that N is the element that gives a largest change in remnant parameter.

5.4 CS 31082

One thing to see for this star before analyzing each parameter, it can be seen that there are more elements to begin with due to higher [Fe/H]. The only removed elements are N and O that give zero results from Starfit, and Cr is removed since Starfit by default uses lower limits for that element. The results can be seen in table 6. There are several elements that are f-type. Unlike the f-type elements for the other stars, many of these f-type have a lot of perturbance in parameter value with small changes in dex. These are therefore strong f-type elements. The mass parameter values has many elements over 2 $\frac{M_\odot}{dex}$, but many of these are fairly flat. There are two elements over 4 $\frac{M_\odot}{dex}$, but when we inspect Co it is very flat. The data points that increases its value is that when the mass parameter changes it changes from 0 to 20 $M_\odot$; however, it is over 1 dex from starting point. The only other value over 4 is C and by examing it we see that it changes alot. The three f-type elements are also very important when we examine it, especially Ni which changes from 8 $M_\odot$ to 40 $M_\odot$ when the abundance changes by less than 0.5 dex. Ni, K and Na are special and important, but apart from that C is the most important element for mass determining. The $\frac{\Delta P_{energy}}{\Delta \epsilon_i}$ is very similar for all elements, making it difficult to analyze them based only on the values. Apart from the f-type Ni, which data points range from 0 to 10 in 0.5 dex, and the other two f-type elements which have a smaller range, it is difficult to see which elements have a higher or lower importance for determining the energy parameter. All elements with a value over $|0.7|$ $\frac{\Delta P_{energy}}{\Delta \epsilon_i}$ and C with $|0.56|$ $\frac{\Delta P_{energy}}{\Delta \epsilon_i}$ are equally important; that is Si, Ca, Ti and Mn. Ti is much higher, and if you would have to give one element higher importance, it would be Ti both by looking at the graph and by

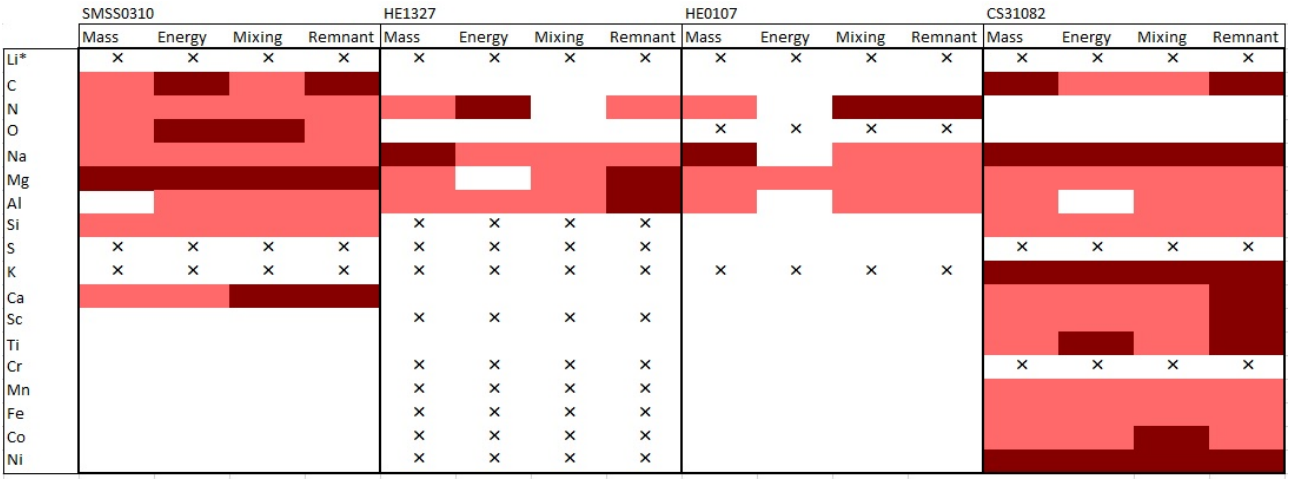

Figure 9: The results for the stars. The dark red squares are the most important elements, light red is not important but is non-zero, white is a zero result and x indicates that no abundance for that element was given.

looking at the value. The mixing parameter is also very difficult to analyze. It is obvious that the four f-type elements are important, as before. When comparing the other elements, it can't be said that one element is more or less important. For the remnant we start off by looking at the elements with a value over $|1|$ $\frac{M_\odot}{dex}$. Mg and Co are flatter than the value indicates and therefore not important. Equally important is Ca, Sc and Ti. The f-type are chaotic even if they don't vary much in value of parameter, so therefore it is even more difficult than before in deciding which is more important in determining remnant parameter.

6 Conclusion

For the SMSS0313 it is obvious when we examine table 3 that C, O and Ca are important for two parameters each, and with Mg playing a role in every one. Al and N hardly play a role at all. To summarize HE1327, looking at table 4, we see that no element can be claimed most important generally for all parameters. What we see is that more elements have no impact at all. When it comes to HE0107, N is the most important element for two of the four parameters, as seen in table 5, where the energy parameter hardly changes at all. N and Na are the two elements we examine for all parameters, and even if Na only is the most important for one parameter we can say that N and Na both are important for the parameters for this star. Finally, we have CS 31082 which has more elements, and thus more elements will be important. Table 6 gives that Na, K and Ni are f-type and therefore important overall. Apart from them C and Ti is important for more than one parameter.

Table 5: Results HE0107, $\frac{\Delta P_j}{\Delta \epsilon_i}$. The letters after each value indicate which classification the graph is according to the description in the method. The values in boxes indicates the most important element for each parameter.

Element	Mass $[M_\odot]$	Energy [B]	Mixing [dex]	Remnant $[M_\odot]$
N	6.42 ± 0.78^b	0	$\boxed{0.33 \pm 0.14^b}$	$\boxed{4.24 \pm 0.56^b}$
Na	$\boxed{-6.86 \pm 1.63^b}$	0	-0.07 ± 0.008^b	-2.26 ± 0.14^a
Mg	-1.94 ± -5.12^d	0.03 ± 0.07^b	-0.101 ± 0.03^b	-1.94 ± 1.3^d
Al	$f-$	0	$f-$	$f-$
Si	1.2 ± 1.1^b	0	0.04 ± 0.03^b	0.79 ± 0.71^b

Table 6: Results CS 31082, $\frac{\Delta P_j}{\Delta \epsilon_i}$. The letters after each value indicate which classification the graph is according to the description in the method. The values in boxes indicates the most important element for each parameter.

Element	Mass $[M_\odot]$	Energy [B]	Mixing [dex]	Remnant $[M_\odot]$
C	$\boxed{-4.23 \pm 0.26^c}$	-0.56 ± 0.096^c	-0.343 ± 0.027^c	$\boxed{f+}$
Na	$\boxed{f+}$	$\boxed{f+}$	$\boxed{f+}$	$\boxed{f+}$
Mg	-0.104 ± 0.08^c	0.42 ± 0.05^c	-0.21 ± 0.1^c	-1.64 ± 0.44^c
Al	-2.22 ± 0.18^a	0	-0.3 ± 0.03^a	0.013 ± 0.0008^a
Si	3.27 ± 2.19^c	0.77 ± 0.31^c	-0.29 ± 0.07^a	-0.02 ± 0.81^d
K	$\boxed{f+}$	$\boxed{f+}$	$\boxed{f+}$	$\boxed{f+}$
Ca	2.7 ± 0.9^c	0.89 ± 0.04^a	-0.16 ± 0.59^c	$\boxed{-1.52 \pm 0.7^b}$
Sc	-0.37 ± 0.08^b	0.51 ± 0.07^b	-0.26 ± 0.03^b	$\boxed{-2.32 \pm 0.98^b}$
Ti	2.99 ± 0.69^c	$\boxed{1.44 \pm 0.24^a}$	-0.09 ± 0.02^d	$\boxed{-3.3 \pm 0.6^b}$
Mn	-2.45 ± 0.56^b	-0.75 ± 0.21^b	0.31 ± 0.06^b	0.71 ± 0.59^b
Fe	0.32 ± 0.34^c	-0.2 ± 0.16^b	0.1 ± 0.2^c	-0.65 ± 0.47^b
Co	-4.99 ± 1.92^c	-0.17 ± 0.05^b	$\boxed{f+}$	-1.04 ± 0.29^b
Ni	$\boxed{f+}$	$\boxed{f+}$	$\boxed{f+}$	$\boxed{f+}$

One thing worth to mention is that the values obtained from the graphs are difficult to understand. A big error isn't necessarily an indication that the value is wrong, but a bigger indication that the data points vary a lot thus making a best fit difficult. A value with low $\frac{\Delta P_j}{\Delta \epsilon_i}$ but high error can be more important than a high value $\frac{\Delta P_j}{\Delta \epsilon i}$ and low error. It is also important to look at the classification. For CS 31082 a couple of elements couldn't be fitted at all, and when observed it could be seen that they fluctuated heavily and therefore was very important, and *a*-type being straightforward and giving one definitive value for the $\frac{\Delta P_j}{\Delta \epsilon_i}$.

When looking at the type it is obvious to notice that whenever a $f+$-type is present it will be the most influental for determining that parameter. The two types that have least influence are *a*- and *d*-type which only is the most important type one time each. It is impossible to state that *a*- and *d*-type always are less important. *b*-, *c*- and *e*-type is equally represented in the most important elements for determining different parameters. The only element that plays the same roll in all four stars is Si, which plays little or no role at all in determining the parameters in comparison to the other elements.

In figure 9 are the results for all four stars with the most important element being dark red for each parameter, non-important elements are light red, elements with a zero-value are white and elements for which no abundance was given are marked with an x. When we compare SMSS0313 and HE1327 in figure 9 we directly see that the two elements that have low or no importance in SMSS0313 (Al and Na) are very important for HE1327. According to this we can say that there are no elements that can be said be generally important in deciding the progenitor supernova parameters for all stars. However when we compare HE1327 and HE0107, since the two stars metallicity are similar, we see that they behave quite alike. The biggest difference is that N is important for the energy parameter in HE1327 but doesn't change the parameter at all in HE0107. CS 31082 has a higher metallicity and behaves quite different from all the three other stars, it is the only star for which elements heavier than Ca gives a non-zero value. One conclusion could be that the metallicity is the largest factor for which elements plays a big or small role for the different parameters.

7 Suggestion for future work

Due to limited knowledge in programming and limited time, I hadn't the chance to use the Starfit code, but only the online version. Because of this I had to change the abundance for each element by hand which took a lot of time. With the code it could have been done by a few lines of code thus saving time. It would be interesting to compare other stars with similar

metallicity to see if it is correct that the metallicity of the star will determine which elements are important in determining the parameters. I have only looked at what happens for one element at a time but it would also be interesting to examine the covariance with two elements together to see if the parameters changes more if two elements are peturbed and if so, which elements has a higher covariance. This can however be difficult since it is quite complicated to look at one parameter/abundance at a time.

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