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Adding Classical Novae Contribution to the Isotopic Scaling model

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Abstract

The Isotopic Scaling model(West & Heger, 2013) provides a complete average isotopic decomposition for our Milky Way as a function of metallicity and it requires an initial Solar Abundance Decomposition as a starting point. The previous Solar Abundance decomposition work is not perfect(West & Heger, 2013), since Classical Novae abundances are ignored. My research intends to improve the current solar abundance decomposition by adding Classical Novae Abundance contribution, then to update the Isotopic Scaling model.

Keywords

Classical Novae, nucleosynthesis, solar abundance decomposition

Cover Page Footnote

I would like to thank Professor Christopher West for giving me this opportunity. I would like to also thank Haoxuan Sun for giving me enormous help on the project.

Adding Classical Novae Contribution to the Isotopic Scaling model

I. Introduction

The Isotopic Scaling model (West & Heger, 2013) provides a complete average isotopic decomposition for our Milky Way as a function of metallicity and it requires an initial Solar Abundance Decomposition as a starting point. The previous Solar Abundance decomposition work is not perfect (West & Heger, 2013), since the Classical novae abundance was combined into a bigger category with the v-process(neutrino nucleus reaction) and Galactic Cosmic Ray spallation abundances, was scaled using a common functional form, and all contributions past ^{7}Li was ignored. This project intends to improve the current solar abundance decomposition by finding the Classical Novae Abundance, then to use the result of the abundance decomposition to update the Isotopic Scaling model.

Unlike supernovae, where a star is completely collapsed, Classical Novae, or Nova , is a surface explosion (that doesn’t destroy the star), which occurs at the H envelope(the outer Hydrogen ring)of a White Dwarf in a binary star system. The Classical Novae is caused by the thermonuclear runaway that initiated from the high-temperature Hydrogen accretion disk, and it is responsible for nucleosynthesis for isotopes between ^{1}H and ^{40}Ca Observed metallicities from classical novae (Frebel 2010) indicate that elements heavier than hydrogen and helium have participated in the explosion. During the explosion, the core materials of the White Dwarf (Carbon and oxygen) mix up with the hydrogen at the hydrogen envelope, which leads to the higher observed value of metallicity at the site of explosion. (Guo 2022)

A free parameter is a variable in a physical model that is not determined by the model itself, but rather needs to be specified or measured from external sources. I used a couple of free parameter values to determine some of the properties of the model.

I used python and X^2_r (Reduced Chi-square) analysis to fit the model to the observed data, the lower the χ^2_r is for a model line, the greater fit the model will have to the observed data.

II. Methodology

Solar abundance decomposition is the process of not only determining the relative amounts of elements (and their isotopes) present in the Sun, but also calculating how each nucleosynthesis process contributes to the abundances for each isotope.

In order to add the Classical nova abundance into solar decomposition, an appropriate classical nova simulation model is required. Traditional Classical Novae simulations are 1-D so they usually assume a spherical symmetry. However, since the Classical novae is a surface explosion on the white dwarf with a point-like source, a traditional 1-D simulation will not yield desired results. I found a model in the literature called the 123-321 model (Jose, 2019), which is a much more complicated computationally rigourous 3-D simulation model. First, it considered the common scenario of core materials mixing at the H envelope, which are largely ignored in the older models. Secondly, the mass of the white dwarf is equivalent to the mass of the sun, which gives a fairly accurate output for our purposes (see abundance of this model in figure 1).

After finding the model for Classical Nova abundance, I calibrated the Classical nova abundance twice in order to incorporate the data into solar abundance decomposition (see figure 2). For the first calibration, I shifted the abundance pattern for our model by a common factor, which is the solar Oxygen-17 abundance over the Oxygen-17 abundance in the model. Here we are using Oxygen-17 because it is one of the most abundant isotopes for the 123-321 model. For the second calibration, we are making sure that all of the abundances sum up to solar abundance.

After adding the Classical nova contributions, the next step is to update the isotopic scaling model.

I created 6 different free parameters, j, f, a,b, m,n. I aimed to derive the value of each of the free parameters by fitting our model line to the observed metallicity dataset by Frebel (2010). Free parameter j represents the fraction of ^{17}O abundance in our sun, and f represents that fraction of Fe-56 abundance in terms of solar abundance. Free parameters m and n are shifting factors for the hyperbolic tangent scaling function of Classical Nova (see figure 4), free parameters a and b are hyperbolic shifting factors for the massive star scaling function. In order to find the best fit line to determine the free parameter values, I used python to loop through all of the possible sets of free parameter values. For each loop, a χ^2_r (reduced Chi-square)will be calculated for each set of free parameter values. For example, suppose that a possible range for the free parameter is set at first, the initial loop will go through all of the integer values. The next step is to narrow down the range for looping by looping all of the values centered around the lowest χ^2_r. After each loop, we are able to narrow down the range for that free parameter further and refine its resolution , then ultimately we would get a free parameter value that has enough significant digits so that the model's best fit line to the data is accurate. Applying this method by looping through the sets of free parameter values, a complete set of values can be calculated. Finally, with each of the free parameter values determined, a scaling plot for classical nova abundance vs. metallicity can be created.

III. Results and Discussion

By fitting the model to the observed dataset (see figure 3), I was able to find out the free parameter values that minimize the χ^2_r (see table 1). A j value of 0.12 indicates that about 12 percent of the Solar ^{17}O abundance is created by Classical nova nucleosynthesis. Moreover, a "f" free parameter value of 0.61 indicates that roughly 61 percent of the solar ^{56}Fe abundance is contributed by Type Ia supernovae. The shifting factors a,b,m,n are also determined with parameter a and b having values of 2.714 and 4.231, j and f having values of 0.124 and 0.613 respectively.

Figure 3 shows the best fit line of our model to the available milky way stellar metallicity data (Frebel 2010), where each star represents a single point in the plot. The horizontal axis shows the metallicity scale, [Fe/H], and the vertical axis depicts the relative abundance of Magnesium in the star([Mg/H]). Elemental magnesium was chosed to become our benchmark for fitting the values because magnesium has the most elemental data in the dataset.

Figure 5 shows the Classical nova scaling plot that we generated using Python code (previous code created by Professor West) using the free parameter values. From it, it is clear that in the range of low metallicity ([Fe/H] < -3), the Classical Nova abundance scaling is approximately linear. As the [Fe/H] metallicity value gets closer to 0 (current solar metallicity), the scaling curve for Classical Nova flattens out in log space, which indicates that the rate of Classical Nova nucleosynthesis for elemental Oxygen is slowing down as we get closer to the current time. The scaling result shows that the overall abundance scaling for classical novae is not linear in log space, which is consistent with the scaling properties with other nucleosynthesis processes. (West & Heger 2013) This scaling curve also proves that the traditional assumption that all of the isotopes abundance scales linear over different metallicity is incorrect.

Table 2 compares the original output for Isotopic Scaling Model to the updated model that I created for selected isotopes. The numbers represent the Scaling model Abundance for each isotope divided by the abundance of the Linear interpolation of each isotope in log space at metallicity Z = -1 and -3. For low mass number isotopes, we can see that the new model's abundance values have minimal deviations compared to the original model (for example, for ^{1}H at Z = -1, the old model's value is 1.000 and for my model is 1.007), but as we get into the higher mass number range, the discrepancies for the two models are relatively large (for example, for ^{12}C at Z = -3, the old model's output is 2.93 and for my model is 1.611, that is a difference of 1.3 in log-space(numerically 20 times higher), which is much higher than the difference for ^{1}H for the two models at both metallicity).

IV. Conclusions and Future Works

I've successfully updated the Isotopic Scaling model and the solar abundance decomposition , and plotted Abundance vs. Metallicity for Classical Nova. It is clear that Classical Nova Abundances for the oxygen element did not scale linearly in log space over time. By fitting the model to the observed metallicity data, I found that 12 percent of the solar ^{17}O abundance is contributed by Classical novae, and 61 percent of the solar ^{56}Fe is contributed by Type Ia supernovae. For future works, I aim to using this method to create scaling models for other nucleosynthesis processes that are left out from the original work(Galactic Cosmic Ray Spallation and the v-process, for example). Also, I can use these metallicity data for each element over cosmic time as the initial conditions of stellar simulations.

References

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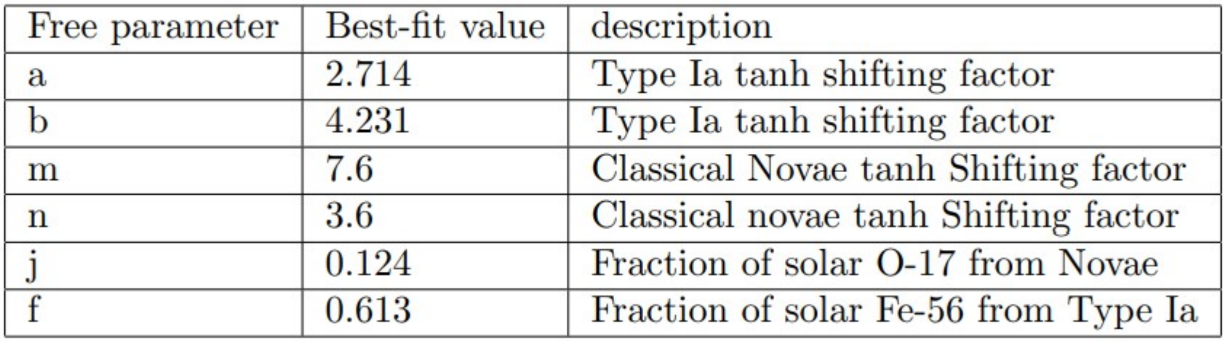
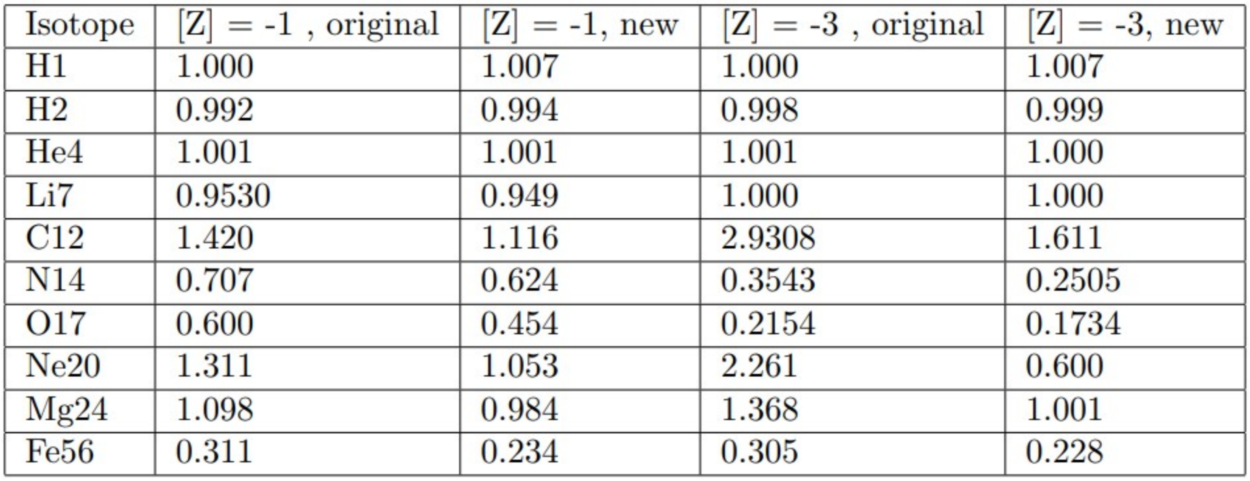
Table 1. Free parameter values



Free parameter	Best-fit value	description
a	2.714	Type Ia tanh shifting factor
b	4.231	Type Ia tanh shifting factor
m	7.6	Classical Novae tanh Shifting factor
n	3.6	Classical novae tanh Shifting factor
j	0.124	Fraction of solar O-17 from Novae
f	0.613	Fraction of solar Fe-56 from Type Ia

Table2. Comparing the original output for isotopic scaling model to the updated model



Isotope	[Z] = -1 , original	[Z] = -1, new	[Z] = -3 , original	[Z] = -3, new
H1	1.000	1.007	1.000	1.007
H2	0.992	0.994	0.998	0.999
He4	1.001	1.001	1.001	1.000
Li7	0.9530	0.949	1.000	1.000
C12	1.420	1.116	2.9308	1.611
N14	0.707	0.624	0.3543	0.2505
O17	0.600	0.454	0.2154	0.1734
Ne20	1.311	1.053	2.261	0.600
Mg24	1.098	0.984	1.368	1.001
Fe56	0.311	0.234	0.305	0.228

Fig.1 Selected Classical novae model isotopic abundance, X-axis is the mass number, Y-axis is the novae abundance over solar abundance in log space

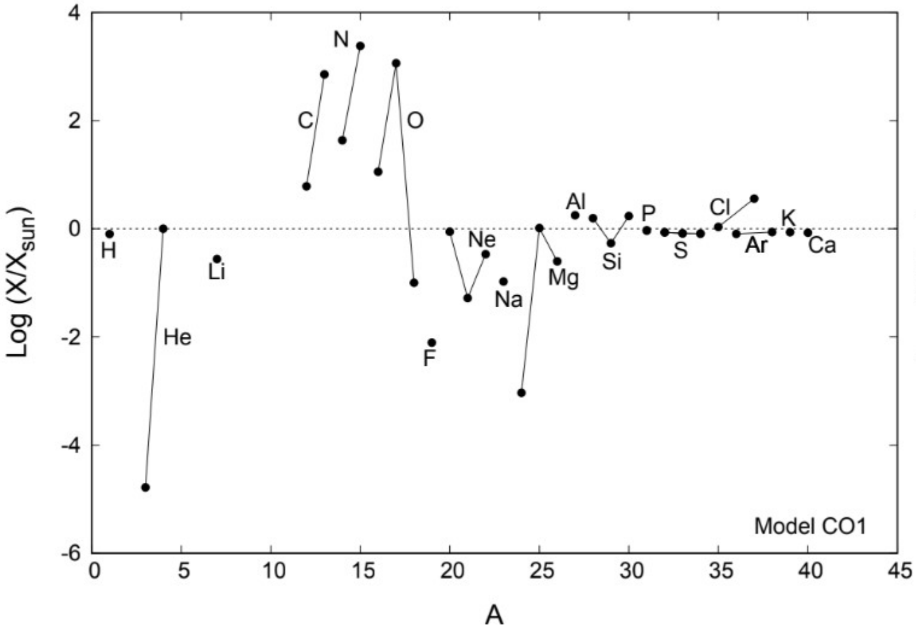


Fig.2 Calibration equations

$$X_A = j \cdot \frac{X_{17}^{\odot}}{X_{17}^{Novae}} \cdot X_A^{CO1} \qquad (1)$$

$$X_{i,f}^{massive} = \left(\frac{X_i^{\odot}}{X_{i,0}^{massive} + X_{i,0}^{Ia} + X_{i,0}^{Novae}} \right) X_{i,0}^{massive} \qquad (2)$$

Fig 3. Fitted model line to Frebel metallicity data

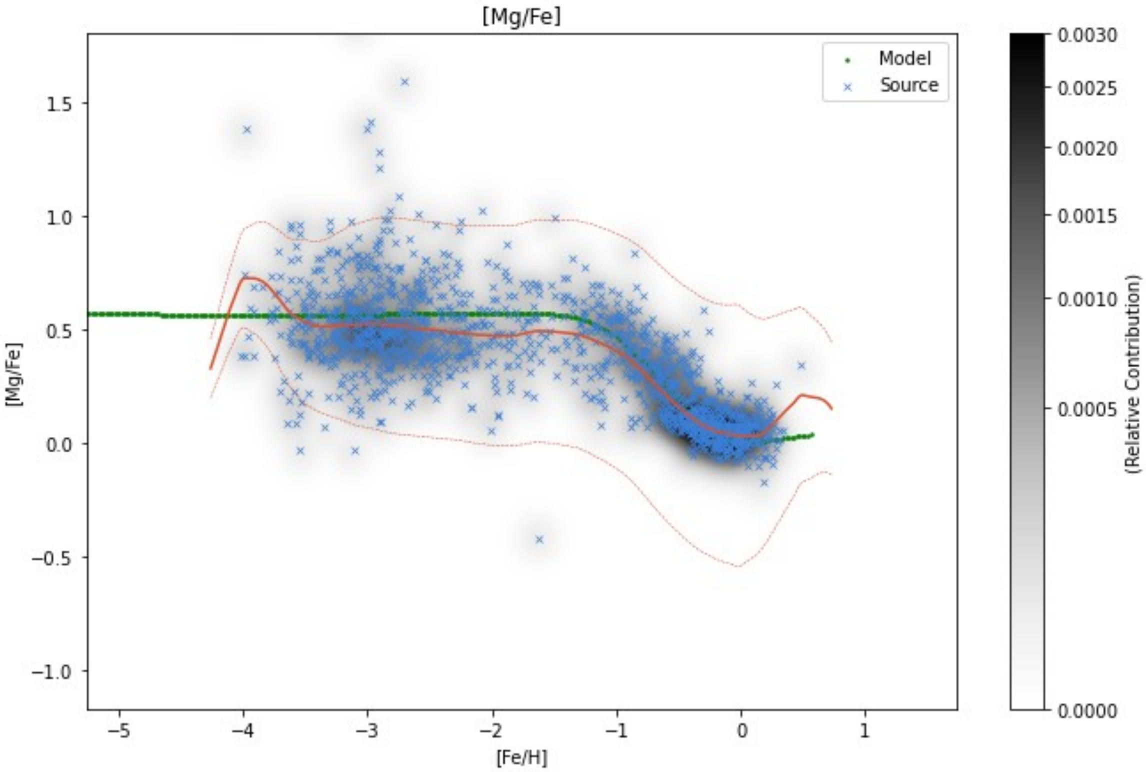


Fig.4 Classical Nova abundance scaling function with free parameter m and n

$$X_i^N(\xi) = X_{i,\odot}^N \cdot \xi \cdot \left[\frac{\tanh(m \cdot \xi - n) + \tanh(n)}{\tanh(m - n) + \tanh(n)} \right]$$

Fig. 5 Classical Novae abundance scaling plot over metallicity