Investigating Abundance Properties of Stars at Different Galactocentric Radii with APOGEE

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We utilize the APOGEE spectroscopic survey of red giant stars to investigate abundance properties in the galactic disk. Our approach involved using multivariate regression to attempt to find single elements and sets of three elements that are strongly correlated with all abundance properties. As a result, we tentatively suggest Mg and Ti-II as examples of highly predictive elements. However, analysis of how abundances vary as a function of r_{gc} indicate that the distribution of abundances is likely bimodal with no closed-form approximation, which we hypothesize is due to the third dredge-up. To gain a better understanding of how chemical element abundances correlate with each other and galactocentric radius, we recommend that future efforts use cluster membership or trajectory data as a means of isolating the two main groups of red giant stars.

INTRODUCTION

The APOGEE project is a large-scale, stellar spectroscopic survey conducted in the near-infrared portion of the electromagnetic spectrum. It consists of two 300-fiber cryogenic spectrographs that operate onboard telescopes at Apache Point Observatory in New Mexico and Las Campanas Observatory in Chile. APOGEE can more easily detect light from stars situated in the dusty regions of the Milky Way. As a result, APOGEE offers detailed chemical and kinematic information for target stars in the disk and bulge.

Understanding the chemical information, such as composition, of stars provides valuable insights into the formation and evolution of galaxies because of processes that are exclusive to the creation of heavier elements and even exclusive to certain stars. The APOGEE Stellar Survey is particularly insightful because of its measurement of a range of chemical abundance elements in the Galactic disk, which upon first inspection, exhibited complex patterns of chemical abundance.

Our preliminary investigation led us to studies that used the same APOGEE DR17 data set. In an analysis of galactic chemical gradients, it was noted that the radial gradients of metallicity and even the elemental abundance ratios in the galactic disk have been found to vary in many of the measured parameters(such as age) indicating that the chemical evolution of the galaxy has not been a smooth or continuous process(Myers 2022). For example, in an analysis of of ratio trends for six alpha elements (O, Mg, Si, S, Ca, and Ti) over iron, radial gradient appeared to steepen with increasing age and even steeper ends, consistent with other data sets and the literature, suggesting non-continuous star formation but chemical enrichment in the inner regions of the galaxy.

In light of previous research, some key elements initially of interest, as they had a variety of implications about galactic formation, were alpha, light, and heavy elements. For example, iron [Fe/H] and nitrogen [N/Fe] as these are important indicators of stellar nucleosynthesis, and hence, their abundance properties in the galactic disk provide important clues about the chemical enrichment history of the Milky Way and the formation and evolution of the disk. We expect iron abundance, for example, to decrease with increasing galactocentric radius. While nitrogen abundance, on the other hand, has a more complex behavior due to primary and secondary productions. We expect nitrogen abundance in regions dominated by secondary productions related to the CNO cycle (Magrini 2018), so we would expect it in higher mass stars which don't stray from their birthplace in the disk due to shorter lifetimes.

These abundance properties, in short, of stars in the galactic disk provide important clues about the physical conditions and processes that governed the formation of the disk and the stars within it. One complication is that since we are strictly surveying red giant stars, whose atmospheric abundances change dramatically throughout their stellar lives. Restricting our search to red giants can also enable us to understand the unique abundance properties of these specific stars.

DATA

Before making any cuts to the data, the survey consisted of 733901 stars. In order to limit our search to typical red giant stars in the galactic disk, we restricted our search to stars with $z < 1$ kpc and $log(g) < 3.8$. To exclude unreliable measurements, we did not look at stars with high relative errors on parallax, expressed via the condition $\frac{\sigma_\pi}{\pi} < 0.2$, or with errors on metallicity $\sigma_{[X]} > 0.1$. To exclude stars far away from the galactic disk and population II stars that are likely not native to the disk, we imposed the conditions $\pi > 0.05$ mas and $[Fe/H] > -1$. This left us with a total of 221244 stars in our dataset. For these stars, we extracted the chemical abundances $[X/Fe]$, parallax measurements, and galactic coordinates for each star. Parallax and galactic coordinates enabled us to calculate the galactocentric radius of each object.

RELATIONSHIPS BETWEEN ELEMENT ABUNDANCES

Before investigating how element abundances varied with galactocentric radius, we first explored whether some heavy element abundances are strongly correlated with others. This would enable us to limit our future analysis to just a few elements, allowing for more direct visualization and potentially simpler linear models of element concentration against galactocentric radius. We used a multivariate linear regression method to assess the strength of correlations. Based on the typical r^2 values of these correlations, we decided to limit our search to 3-element pairs. This assumed some underlying power-law relationship between abundances of the form $[D]^\delta = [A]^\alpha + [B]^\beta + [C]^\gamma$. For every combination of 3 elements, we regressed them against every other element of 22 elements in the dataset and took the average r^2 to measure strength of correlation. The following are the element combinations that yielded the highest average r^2:

set of 3 elements	average r^2
Mg, Ti-ii, Fe	0.33393
Mg, Ti-ii, V	0.33285
Mg, V, Co	0.33213
Mg, V, Ce	0.33100
Na, Mg, Ti-ii	0.32881
Na, Mg, Ce	0.32535
Mg, Ti-ii, Mn	0.32391
Mg, Ti-ii, Co	0.32240
C, Mg, Ti-ii	0.32122
Mg, Ti-ii, Ce	0.32072

We note that no set of 3 elements is dramatically better at predicting abundances than all other sets of 3 elements. However, all 10 of the 10 best sets include Mg, and 7 out of 10 include Ti-ii. This is evidence that stellar Mg and Ti-ii abundances are strongly correlated with most other element abundances. However, this average r^2 is still on the order of 1/3, indicating that variation in these trios of elements can at best explain 1/3 of the variation in other abundances. This is likely due to large amounts of intrinsic scatter in metallicity arising from the complex internal processes in AGBs, stochastic distribution of supernovae, and complicated heavy element loss patterns in planet formation.

Nevertheless, we decided to more thoroughly search for elemental abundances that strongly predict others by noting which elements most frequently predict other abundances nearly as well as the best set of three. We (arbitrarily) set the cutoff at an average r^2 of 0.3.

While Mg and Ti-II seem particularly good at predicting abundance properties, the fact that these average r^2 are fairly close means we decided to check how several elements correlated with galactocentric radius, namely C,

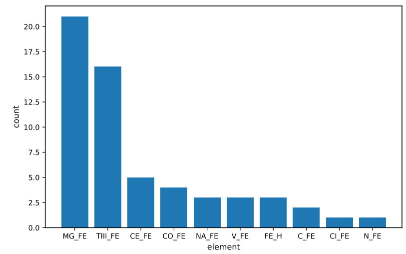

FIG. 1. Number of times in which each element appears in combinations that predict other element abundances well ($\bar{r^2} > 0.3$), shown for the 10 best elements. Mg and Ti-II appear far more often than others.

O, Mg, V, Ti-II, Fe, Co, and Ce. We chose these elements mainly because they appeared somewhat often in the best sets of predictors, but we specifically chose C and O because they are the principal metallic products of stellar nucleosynthesis and therefore might be a good measure of underlying stellar properties.

Limitations

Our decision to use multivariate linear regressions has two major limitations. First, we were unable to weight by error (or account for the errors in any way) because there is no preexisting package to perform multivariate linear regression that accounts for errors. More importantly, these abundances are not linear or power-law functions of each other, as can be seen in the following representative plot of Mg vs. Ti-ii:

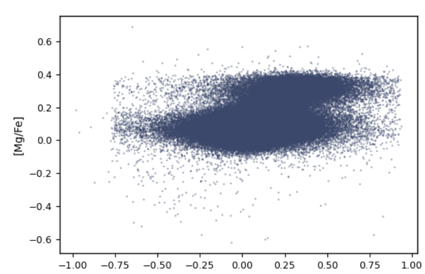

FIG. 2. Plot of [Mg/Fe] vs. [Ti-II/Fe]. There are two populations here, one with [Mg/Fe] around 0.3-0.4 dex, and the other around 0 dex. The population with higher Mg abundance tends to have higher Ti-II abundance, but this relationship is weak.

There appear to be two populations of stars here with mostly uniform abundances of Mg. The potential implications of this bimodal distribution are discussed in the following section. Unfortunately, we were not able to separate this survey into two populations to study separately. First of all, the survey did not provide data about orbital actions, trajectories, or cluster membership, so we had no way of determining whether these stars were of different origin. As our later analysis argues, if this structure is due to the third dredge-up, those data may not have been helpful anyway. More simply, it is difficult to quantitatively and rigorously divide these stars into two populations. It might be possible to make a guess based on [Mg/Fe] by inspection, but considering other element abundances and taking into accound the large intrinsic scatter of these populations such a division would be unlikely to yield meaningful results.

RELATIONS BETWEEN METALLICITY AND RADIUS

We next attempted to find an overall relationship between metallicity and galactocentric radius. We again used a linear regression, therefore assuming some power-law relationship of the form $r_{gc} = [A]^{\alpha}$. We first tried this for the single elements above, but found essentially no relationship. The best r^2 came when measuring [C] against $r_g c$ (0.1), but the model was clearly mis-specified and left us with a line of best fit that did not match the apparent visual trend of the data.

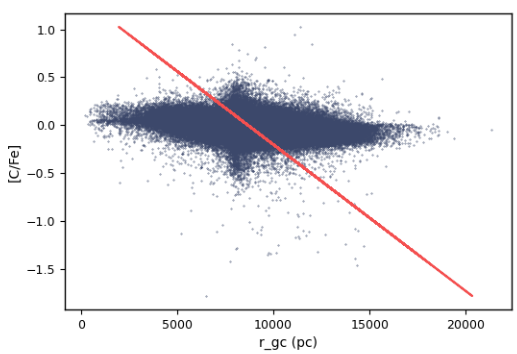

FIG. 3. Attempt at regressing r_{gc} against [C/Fe], with the supposed trendline shown in red. While the linear model is obviously mis-specified, we can still understand the structure of this plot qualitatively.

The issue here is that our data is not distributed linearly. There is a large population of stars with roughly the same $[C/Fe]$ and another population of stars with roughly the same radius, roughly 8 kpc or in the solar neighborhood. We hypothesize that this may be due to a detection bias where only brighter stars are visible as the distance from the Sun increases, decreasing the diversity of those populations. It is also notable that for the stars with [C/Fe] 0, there is a small population of stars that appears to be clustering at a slightly higher value. This is more visible in the graph of [Mg/Fe] vs. $r_g c$ shown in Figure 4.

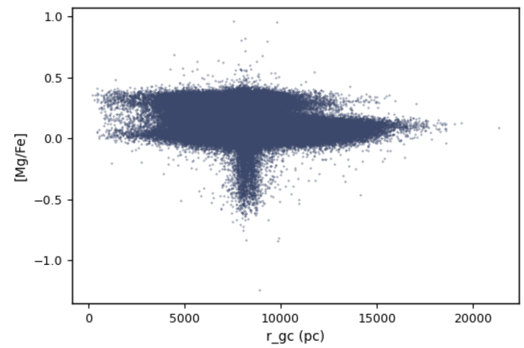

FIG. 4. Plot of [Mg/Fe] vs. r_{gc}. There is clearly a smaller population of stars with abundance clustered around 0.3-0.4 dex, in addition to the larger population clustered around 0 dex.

Given that this is a survey of red giant stars, we hypothesize that this is due to dredge-up events. Some of these red giant stars will have undergone the third dredge-up, where s-process events and carbon are transported to the surface in relatively large quantities. This also explains why the effect is larger for elements such as C and Mg that are created via fusion than elements like Fe (shown in Figure 5) that are created via neutron capture–because abundances of fused elements in the core are so high, they can have a much more dramatic impact on surface abundances.

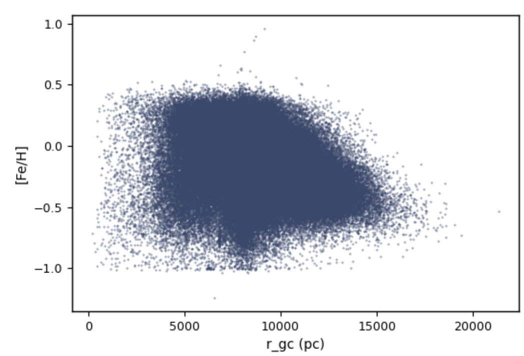

FIG. 5. Plot of [Fe/H] vs. r_{gc}. Abundances appear to be uniformly distributed with no relationship to radius. This may be evidence that the band structure in other element abundances arises from the third dredge-up.

DISCUSSION

Despite thorough analysis, We were unable to find evidence of any closed-form, power-law relationships between chemical element abundances or between any of those abundances and galactocentric radius. Nevertheless, further examination of these variables reveals important differences between AGBs that are more or less bimodal. Notably, there appears to be a minority of AGB stars whose abundances of C, Mg, and other elements formed via nuclear fusion, are greatly elevated due to the third dredge-up. While abundances of Ti-II and especially Mg appear to be strongly correlated with other element abundances, these relationships are weak (average r^2 0.33) and unreliable due to the inherent piecewise distribution of the population.

Future efforts could improve this analysis by using information such as orbital trajectories and cluster membership to separate AGB stars into populations based on location. Restricting this survey to single clusters with more underlying history in common would potentially make this bimodal distribution more evident. In addition, with precise enough measurement of abundances over an extended period of time, stars in the third dredge-up may be identified by direct observations of the rate of change of abundance. Conducting surveys of this type could also be done on main-sequence stars to measure the correlations of abundances at the start of stellar lifetimes and in the ISM. This would also be a good way to trace overall changes in chemical element abundances as a function of radius and time, since these stellar atmospheres will largely reflect the compositions of the clouds from which they were formed.

REFERENCES

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