Variation in the Composition of Cool Stars

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Abstract. Understanding the chemical composition of cool stars in the solar neighborhood is vital to answering key formation and evolutionary questions for not only our local universe, but also for planets orbiting those stars. However, over the last few decades, abundance measurement techniques have changed – such as line lists, atmospheric models, and adopted solar abundances, introducing systematic and stochastic differences between data sets. These differences make comparisons between data sets, let alone stars, very difficult to quantize. I will discuss abundance data from a homogenized compilation of literature sources for ∼3000 stars found within 150pc of the Sun, as part of the Hypatia Catalog. This large collection of chemical abundances allows for a more copacetic understanding of stellar compositions, without bias towards a given group or technique. I will also present abundance results from a collaboration with multiple, international groups who analyzed the same high-resolution spectra using a variety of techniques. Our conclusions from their analysis, as it pertains to the field, suggests that while there are many discrepancies between groups, a standard method of measuring abundances may be in order. With help from the community, the stellar abundance issues may be disentangled to provide an accurate portrayal of the compositions of nearby stars.

1. Introduction

Measuring element abundances in nearby stars is a relatively old technique in astronomy, such that the majority of the current models were originally developed in the 1970s. However, actually calculating the abundances is an intricate process with an equally complicated result. In general, stellar abundances are defined as a logged ratio of ratios, namely: [X/Fe] = $\log{(N_X/N_{Fe})_*} - \log{(N_X/N_{Fe})_\odot}$, where N_X and N_{Fe} are the number of atoms of element-X and iron per unit volume, respectively, normalized to 10^{12} hydrogen atoms. The elements within the star (*) are compared to those same elements within the Sun ($\odot$) resulting in the units of dex, typically indicated using the square brackets.

In this proceeding, I will describe the current state of the stellar abundance field and the results produced by different groups. I will discuss the in-depth analysis that my colleagues and I are currently undertaking, as part of an international collaboration, in order to better understand the differences between currently employed abundance models and techniques. Finally, I will offer some insight into possible corrections that may lead towards abundance standardization within the astronomy community.

2. Comparing Stellar Abundances using the Hypatia Catalog

Over the last couple of years, I have compiled abundance measurements for 50 unique elements from 84 literature sources covering 3058 main sequence (FGK-type) stars within 150 pc of the Sun in order to form the Hypatia Catalog (Hinkel et al., 2014). Not only does Hypatia elucidate the coverage, and lack thereof, of elements across the periodic table, it also provides insights into the measurement methods employed over the decades. For example, some surveys are from a single telescope while others employ multiple. Resolutions of the data vary from $\Delta\lambda/\lambda \approx 30\,000$ (Gebran et al. 2010; Kang et al. 2011) to 120 000 (Ramírez et al. 2007, 2009). In addition, a number of techniques for the stellar atmospheres, determination of equivalent widths of the absorption lines, and overall measurement of the element abundances are employed by different groups in a combinatorical fashion (please see Section 2.2 of Hinkel et al. (2014) and Table 3 for a more thorough analysis).

When a group determines a new set of stellar abundances, the historical procedure is to compare the new dataset with widely accepted benchmark abundances of similar-type stars, for example Edvardsson et al. (1993) and Valenti & Fischer (2005). However, there is no standardized method when comparing new data to old. Statistics are sometimes used to quantize deviations, other times the surveys are graphically compared. Some have found that agreement between the datasets was "obvious" without additional clarification. Unfortunately, disparities between abundance measurements are sometimes ignored outright, citing an "obvious," yet unqualified, similarity or admitting that "from a relative point of view" the studies are copacetic.

Figure 1 (Hinkel et al. 2014) shows a graphical comparison of abundance measurements from the Hypatia Catalog as determined by separate groups, with respective error bars. The stars and elements were chosen to be representative, purely because they were commonly measured and allowed for a better statistical comparison. There is a marked discrepancy between the five elements (Na, Si, O, ScII, and Al), where many measurements do not overlap to within cited error. More surprisingly, there are also large issues with regard to [Fe/H] (the element for which the term "metallicity" has been bogarted by the community with the idea that it is well-understood and can act as a proxy for the other "metals").

Within the Hypatia Catalog, the average *spread* was 0.14 dex, or the maximum variation of abundance measurements for the same star and element reported by different literature sources. However, catalogs do not necessarily use the same solar abundance scale (e.g. Anders & Grevesse 1989; Asplund et al. 2009) when determining abundances. In Section 3.2 of Hinkel et al. (2014), my collaborators and I tried to ameliorate the overall spread by addressing the solar abundance scale employed by different surveys. We removed the solar abundance scale used by each individual group and re-normalized to a standard solar scale, namely

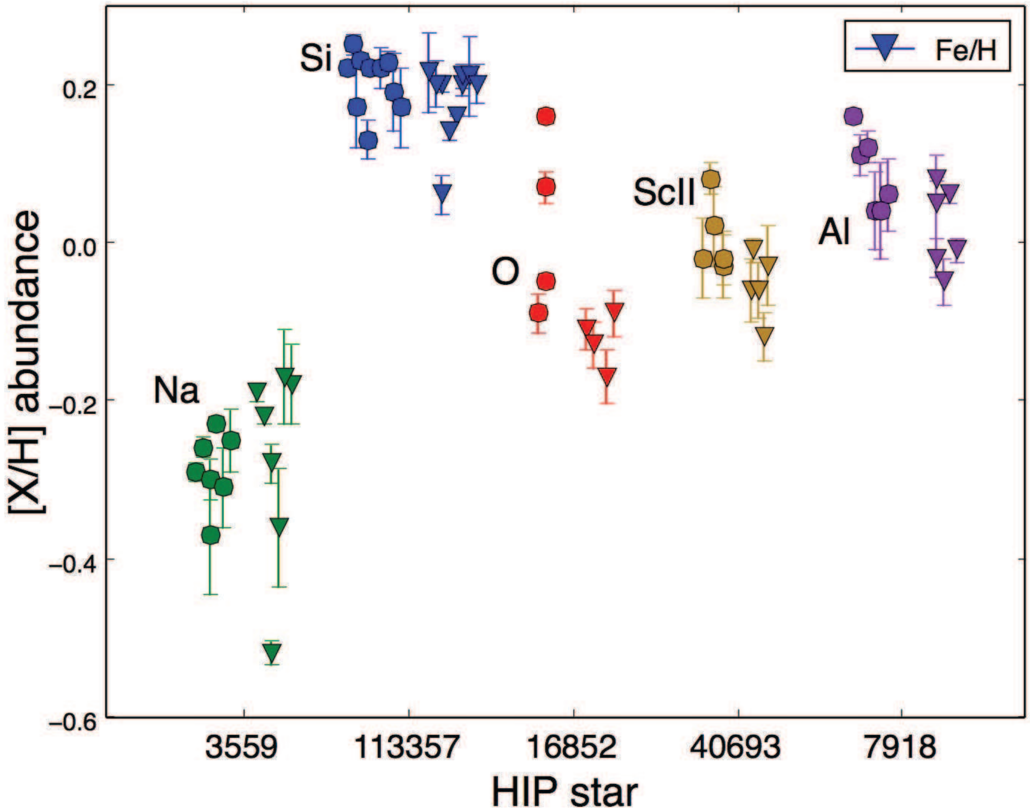

Figure .1: A reproduction of the top panel of Fig. 3 from Hinkel et al. (2014) showing the variation in abundance measurements by different groups for 6 elements (circles are indicated on the plot, triangles are Fe) in 5 different stars. All measurements are as quoted by each literature source with respective associated error bars.

Lodders et al. (2009). The mean of the absolute difference between the original data and the renormalized abundances was 0.06 dex, which is on par with the error bars associated with the majority of elements. This significant change indicates that the solar abundance scale has a direct contribution to the variation of the abundances seen between groups. However, the average spread for the renormalized abundances was 0.15 dex, meaning that the similar solar scale did not affect the spread, only the individual abundance determinations.

3. International Collaboration

Through the "Stellar Stoichiometry: Workshop Without Walls" (Desch et al. 2014; Young et al. 2014) held at Arizona State University, five groups around the world were given the same stellar spectra in order to analyze the abundances of four unique stars: HD 202206, HD 121504, HD 361, and HD 10700. The goal was to better understand how the methods, stellar parameters, and employed line lists affected the element abundance measurements. To this effect, the groups were asked to analyze the abundances multiple times, doing so autonomously (Run 1), with standard stellar parameters (Run 2), a standard line list (Run 3), and both standard parameters and line list (Run 4). The stars were chosen such that the results would also be comparable to literature results as well as cover a wide [Fe/H] range, where HD 202206 was more iron-rich while HD 10700 was the most iron-poor. The spectra was both velocity shifted and continuum normalized before given to participants, who were then instructed to provide all information (including individual equivalent width measurements) and decisions that they made during the reduction process.

Preliminary results are given in Figure 2, where Si/H (left) is plotted with respect to the different runs measured by each group. The determination of Si/H was very consistent between groups, with minimal spread, and clearly shows the distinctions in "metallicity" between the stars (namely that they are easy to distinguish horizontally). However, it should be noted that even with these excellent results, Run 3 showed more spread in the abundances than both Run 1 and 2. In comparison, Mg/H is shown on the right of Figure 2, with a large spreads existing for HD 10700 in Run 1, HD 361 for Run 2, and all stars but HD 361 for Run 3. The spread was reduced somewhat for Run 4, however, standardizing both the stellar parameters and the line list did not have the intended consequence of reducing the spread across the board for Mg/H.

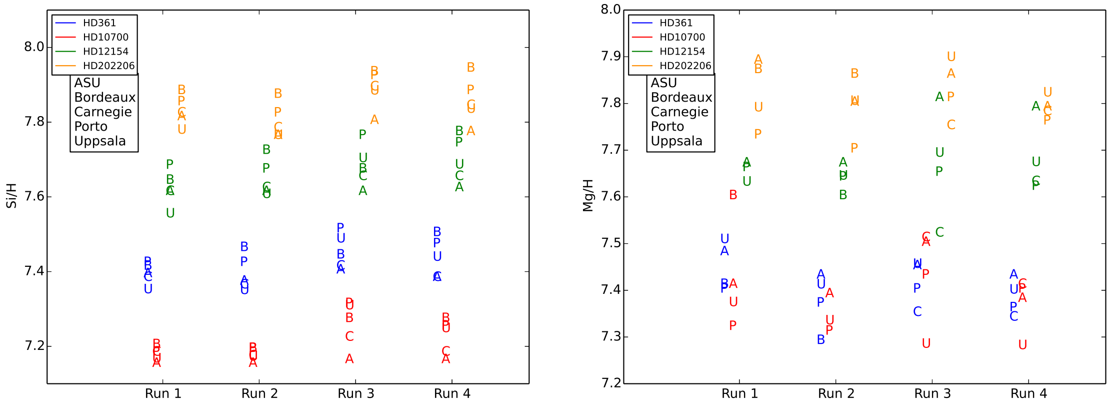

Figure .2: Non-solar normalized abundance determinations for the four stars (indicated by color) as determined by a range of groups (indicated by the first letter on their institute) employing a variety of measurement techniques. Multiple runs were conducted in order to see the variation between autonomous (1), standard stellar parameter (2), standard line list (3), and standard parameter and line list (4) determinations.

A total of 13 of the more common element abundances were analyzed in order to better focus our future analysis. For the autonomous run, the average spread between elements for all groups was 0.41 dex, where the maximum was 1.22 dex for both Cr II and O. For Run 2, the average spread across elements decreased to 0.27 dex, although Cr II had the worst at 1.24 dex. Runs 3 and 4 had the same mean at 0.44 dex, indicating that the line list was a negative dominating factor for the abundance determinations. In both cases, O had the worst spread at 1.73 dex and 2.01 dex, respectively. Tentative results show that, when the stellar parameters are standardized, for example through astroseismology measurements, abundances across different models are more comparable. Additional work is currently being undertaken to analyze the abundances and their respective spreads more thoroughly, looking specifically at the equivalent widths for each line determined by each group to shed light on the surprising outcome of Run 3. The upcoming paper (Hinkel et al. 2014b, in prep) is currently in preparation and will expand upon the concepts explored here; additional comments or suggestions are welcome.

4. Summary

Stellar abundances are complicated, by definition. Not only is high resolution ($\Delta\lambda/\lambda \geq 50\,000$) data required to determine accurate measurements, but there are a number of complicated steps that eventually result in element abundances. It is time that the community try to better understand the methods that we employ and how they compare to one another. As indicated by the spread in the data, the issues between techniques, which may be systematic, are real and have yet to be properly addressed. A more standard, homogenous technique may be needed so that abundances between surveys, as well as between stars, will be more rigorous. Fortunately, through an international collaboration, we are taking positive steps forward to better understand the methods as well as the science.

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Natalie Hinkel covered the details of her Hypatia database.