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The Salty Sun: Stellar Sodium Abundance of Earth's Home

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1. INTRODUCTION

In the hunt for other life in the universe, one must first understand the ground these potential species may stand on. Due to the distance of other stellar systems as well as the relative size of planets, it is difficult to directly probe these other worlds. Luckily for astronomers, one can gain a good inference to the chemical composition of planets from their host star. Thus in order to understand the chemical abundance of extrasolar planets, the chemical composition of the star must be constrained.

To constrain the chemical composition of the star, we must find the log abundances of atomic and molecular species of interest. By becoming comfortable with this process, we can look for abundances of a variety of different elements and molecules of extrasolar planets and their host stars.

For this project, we use solar absorption spectra to solve for the log abundance of sodium. We make use of the $5896 \mathring{A}$ sodium doublet line (D line) throughout this paper to conduct our calculations, and aim to compare our log abundance to previous literature.

2. DATA

Data used in this work is provided by the BASS2000 Solar Survey Archive. Particularly, the wavelength in which our specific set of data is located is was provided by Delbouille et al. (1973). A portion of the solar spectrum is shown in Fig. 1, which focuses around the second peak of the sodium doublet line at $5896 \mathring{A}$.

3. METHODS

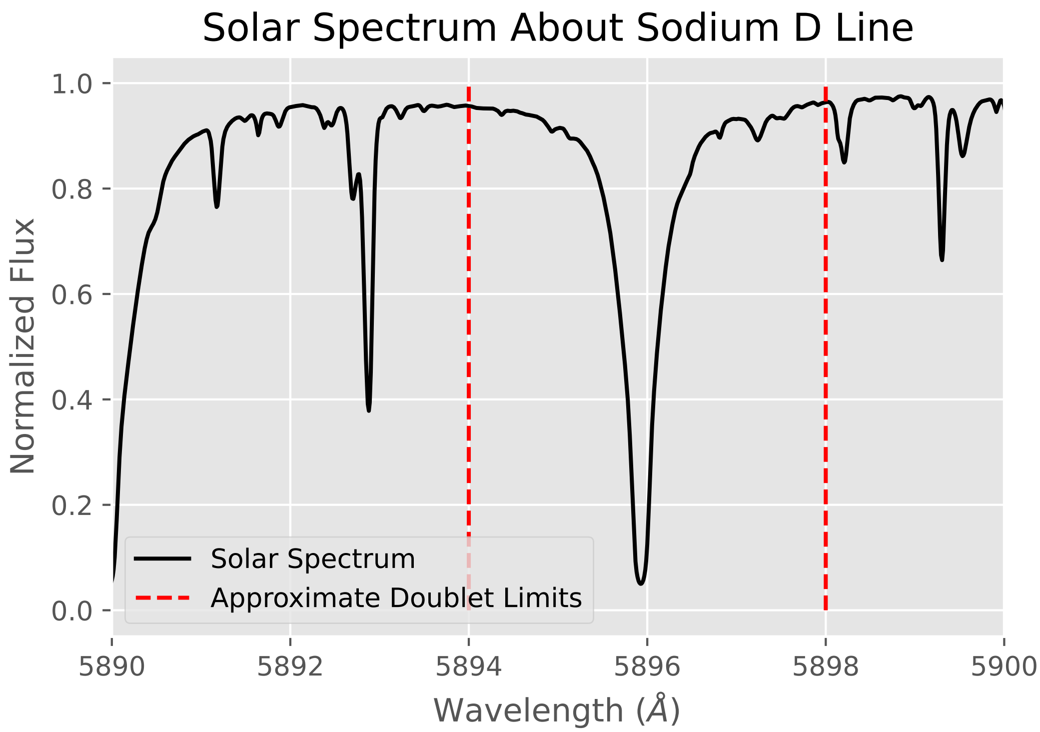

Figure 1. Stellar spectrum for the sun about the 5896$\AA$ sodium doublet line.

3.1. *Sodium Atoms in Ground State*

The first step in calculating the stellar abundance of sodium is determining how the amount of Na atoms in the ground state. We utilize the 5896$\AA$ sodium line as shown in Fig. 1 and the growth curve in Fig. 2 to perform this calculation. The total amount of ground state Na can be calculated from

$$\mathrm{Log}(EW/\lambda) \tag{1}$$

$$\mathrm{Log}\left[N \cdot f \cdot (\lambda/5000\AA)\right] \tag{2}$$

where EW is the equivalent width of the Na line, λ is the wavelength, N is the number of ground state atoms, and f is the oscillator strength. We make the assumption that the oscillator strength for the 5869$\AA$ doublet line is approximately equivalent to that for the 5860$\AA$, being $f = 0.65$.

First, we calculated the EW using a step-wise integration method to approximate the area under the absorption feature, obtaining 0.65$\AA$. We then put the EW into Eqn. 1 to calculate -3.96 and

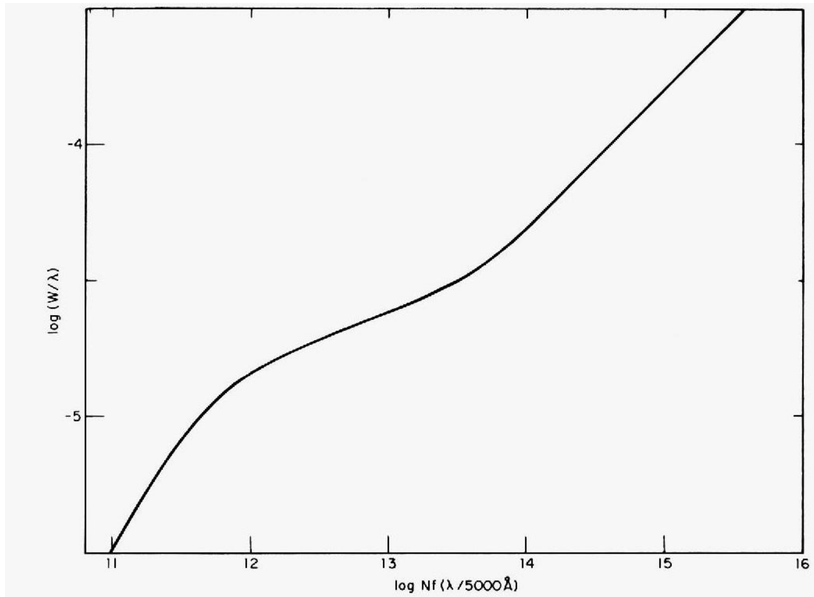

Figure 2. General growth curve for the sun (Figure from Aller & Goldberg (1971)).

matched this value with the growth curve in Fig. 2 and solved Eqn. 2 to calculate 14.6. With these values, we then rearrange and solve Eqn. 2 for $N = 5.19 \times 10^{14}$ atoms.

3.2. *Boltzmann Equation*

We estimate the amount of excited to ground state sodium atoms, which is given by the Boltzmann Equation below:

$$\frac{N_{3p}}{N_{3s}} = \frac{g_{3p}}{g_{3s}} \exp\left(-\frac{E_{3p} - E_{3s}}{k_B T_{eff}}\right). \tag{3}$$

Where $\frac{N3p}{N3s}$ is the ratio of excited state to ground state sodium atoms, $\frac{g3p}{g3s}$ are the Landé g-factors, E_{3p} and E_{3s} refer to the energy at the 3p and 3s states, k_b is Boltzmann's constant, and T_{eff} is the effective temperature of the sun.

We also adopt values for the Landé g-factor for the $3s_{\frac{1}{2}}$ and $3p_{\frac{1}{2}}$ states of 2.002296 and 0.66581, respectively (Arimondo et al. 1977). We use a rough estimate for the effective stellar temperature as $5800K$, and values for the energy states as $-5.14eV$ and $-3.04eV$ for E_{3s} and E_{3p}, respectively.

Plugging each of these values into Eqn. **??** and solving gave us a calculated value of 4.98×10^{-3}.

3.3. *Saha Equation*

We obtain the ratio of neutral sodium atoms to ionized sodium atoms by using the Saha equation given below:

$$\frac{Na_{II}}{Na_I} = \frac{2k_bT_{eff}}{P_e}\frac{Z_{II}}{Z_I}\left(\frac{2\pi m_e k_b T_{eff}}{h^2}\right)^{3/2}\exp\left(-\frac{\chi}{kT}\right) \tag{4}$$

Where $\frac{Na_{II}}{Na_I}$ is the aforementioned neutral to ionized sodium atom ratio, k_b is Boltmann's constant, T_{eff} is the effective temperature of the sun, P_e is the electron pressure. Z_{II} and Z_I are the partition functions for neutral and ionized sodium, m_e is the mass of the electron, h is Planck's constant, and χ is the ionization energy. We adopt $1N/m^2$ for P_e and values of 1.0 and 2.4, for Z_I and Z_{II}, respectively. Rough estimates for the effective stellar temperature and ionization energy are also used, being $5800K$ and $5.1eV$. From Eqn. **??** we obtain a ratio of $\frac{Na_{II}}{Na_I} = 2365.14$.

3.4. *Column Density of Na*

Next, we used the values obtained from Sections 3.2 and 3.3, along with our calculated number of sodium atoms in the absorbing state, to calculate the column density of sodium given by the equation below:

$$N_1\left(1+\frac{N_2}{N_1}\right)\left(1+\frac{Na_{II}}{Na_I}\right) \tag{5}$$

Where N is our calculated value of absorption state sodium atoms from Eqn. 2, $fracN_2N_1$ is our calculated value of excited state to ground state sodium atoms from Eqn. 3, and $\frac{Na_{II}}{Na_I}$ is our calculated value of neutral to ionized sodium atoms from Eqn. 4. Plugging these into Eqn. 5 returns a column density of $1.38 \times 10^{18} cm^{-2}$.

4. RESULTS

Using the column density calculated in Section 3.4, the sodium abundance in comparison to that of hydrogen can be obtained. We assume the stellar column density of hydrogen is $N_H = 6.6 \times 10^{23} cm^{-2}$. Taking the ratio of our Na value to that of H for the sun results in a mole ratio of:

$$\frac{N_{Na}}{N_H} = 2.08 \times 10^{-6}.$$

This can then be used to determine the log mole ratio of sodium with

$$\epsilon_{Na} = 12 + \text{Log}\left(\frac{N_{Na}}{N_H}\right),$$

where N_{Na}/N_H is calculated above. The resultant log abundance of sodium is thus $\epsilon_{Na} = 6.32$.

5. DISCUSSION

Our resulting Na log abundance value is consistent the literature, with Scott et al. (2015) determining the Na log abundance to be 6.21. They use a much more in depth method to determine their abundance, using 3D hydrodynamical models of the photosphere (Scott et al. 2015). Due to the closeness of these two values, we can confirm that our simplistic methodology gives us agreeable results and can be used to predict abundances of other solar elements given their absorption spectra. This process can be repeated using absorption spectra, along with transmission and emission spectra to predict the abundances of a variety of atomic and molecular species in the atmospheres of extrasolar planets and their host stars. Though this methodology is much easier to perform with objects in our solar system and hot planets with short orbital periods such as KELT-20b (Petz et al. 2023; Johnson et al. 2023) and WASP-39b (JWST Transiting Exoplanet Community Early Release Science Team et al. 2023), with more expertise and more precise data given by the *James Webb Space Telescope* as well as the newly proposed *Habitable Worlds Observatory*, we hope to be able to use this process to look for biogenic molecules to aid us in the search for life.

6. CONTRIBUTIONS

- *Aiden Zelakiewicz* - AZ lead the paper, contributed to the code and derivations, as well as assisting in the creation of the presentation and presenting.
- *Sydney Petz* - SP lead the presentation, presented, contributed to the paper, and assisted in the code. SP wrote the Discussion section and assisted the Introduction for the paper.
- *Justin Anderson* - JA wrote and computed the code for the project, obtaining the sodium abundances. JA also assisted in the authorship of the Methods section, leading Sections 3.2-3.4.

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