

Determining Chemical Composition of the Sun

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All figures referenced in here are in the other pdf called Solar Spectrum Figures.

1 Abstract

This study seeks to determine the chemical composition of the Sun. We observed the Sun on the morning of Friday, May 5th, 2023, and used a spectrometer to collect both high and low-resolution first-order spectral lines of the Sun. With these, we determined the wavelengths of the absorption lines and compared these to the absorption lines of expected elements in the Sun to identify its composition. We found the number of elements in the Sun which are laid out in 5.1 table 4 and match many of the elements we expected to see.

2 Introduction

With the spectrum of a star, we are able to determine various properties of it including the chemical composition of the star. From the spectrum, we can see absorption lines at various wavelengths which appear as drops in the intensity of the light. This is caused because elements have different energy levels so they will absorb the light with enough energy to excite their electrons. If we know what these wavelengths are, we can look at the spectrum of a star and see which elements the drop in its spectrum corresponds to. This is because as light leaves the star and travels to the surface it could be absorbed so the intensity drops in that wavelength which is an indicator that it contains that element [1].

The main purpose of this experiment is to determine the chemical composition of the Sun by using its spectrum. With the spectrum, we can also determine the class of star that the Sun is and determine the temperature of the Sun by fitting our spectrum to the black body equation.

In the following sections, we describe our observation of the Sun, the processing of our data, our results, and finally a discussion of our results with the literature.

3 Observation

3.1 Conditions & Equipment

Data was collected on Friday, May 5th, 2023 from 9:20 am to 10:20 am. The weather was slightly overcast, so the intensity of sunlight varied throughout the hour. Our materials consisted of a spectrometer, a CCD camera, and a mercury-argon (Hg) lamp. The spectrometer uses a micrometer to adjust the angle of its mirror so that different wavelength ranges shine on the CDD. The difference between high and low resolution comes in here. On high resolution, the mirror spreads out the light over a larger area so that the differences between similar wavelengths are more apparent. This does narrow the range that we can observe in high resolution for which we expect to be within 40 nm to either side of our central value, determined by the micrometer setting. In low resolution we expect to be within 320 nm [2] An adjustment of 1 mm on the micrometer corresponds to a change in wavelength of 100 nm. The settings in both high and low resolution that we used are shown in table 1 with the expected wavelength ranges for each.

Micrometer setting	High Resolution λ	Low Resolution λ
4.0 mm	360-440 nm	
4.4 mm	400-480 nm	
4.8 mm	440-520 nm	
5.2 mm	480-560 nm	
5.6 mm	520-600 nm	240-880 nm
6.0 mm	560-640 nm	
6.4 mm	600-680 nm	
6.8 mm	640-720 nm	

Table 1: These are the relations between the micrometer setting and the estimated wavelength range in high and low-resolution modes. I include only the low resolution for 5.6mm because this is the only one we used in low resolution.

3.2 Procedure

Start by setting the micrometer to 5.6 mm and the spectrometer to low resolution. This centers us in the Sun's visible spectrum and gives us an overview of what we are looking at. We begin each data collection by first recording the spectrum of only the Hg lamp. This will help us identify wavelengths later. Place the Hg lamp directly in front of the spectrometer and cover them both to block out the sunlight. Then take an exposure so that the max count on the CCD is between 10,000 and 30,000. Next, Without knocking the spectrometer or CCD, remove the cover and the lamp. Then take an exposure of the sunlight, again for a max count of 10,000 to 30,000.

After successfully capturing those two images, low resolution is complete, so switch the spectrometer to its high-resolution setting. Repeat these steps of taking a Hg spectrum and then the Sun's spectrum for the various micrometer settings given in table 1. Only one good data taking is needed for each setting but make sure nothing is changed when moving the lamp and take multiple if the counts are either too high or too low. Table 2 shows our exposure times for each run, with a \times to indicate which runs were rejected for having too many or too few counts.

Resolution	Micrometer Setting (nm)	Source	Exposure (s)	Accepted
Low	5.6	Hg	10	
		Sun	10	
High	4.0	Hg	25	
		Sun	20	
	4.4	Hg	20	
		Sun	15	
	4.8	Hg	20	
		Sun	15	
	5.2	Hg	20	
		Sun	15	
	5.6	Hg	20	×
			15	×
			7	
		Sun	15	
	6.0	Hg	10	×
			25	
		Sun	20	
	6.4	Hg	25	
			25	×
			35	×
			27	
	6.8	Hg	25	
		Sun	25	

Table 2: High-Resolution Configurations. From left to right: the micrometer settings, the source, the exposure time which was used to get a max counts range of 10,000-30,000, and whether or not we used that run's data. If it is marked by a ×, it was because the counts were either too high, so the camera was saturated, or too low so there wouldn't have been enough data to easily distinguish the spectrum from the background. Unmarked runs were used in the analysis.

4 Data Processing

4.1 Obtaining a Spectrum

The data collected from the CCD looks like the image in figure 1. This is the Hg low-resolution run. When taking data the spectrometer automatically takes and subtracts darks for us, so we do not need to do this manually. For each of these images, we begin by cutting out the 10 center rows to work with. We have a high pixel count so we can do this and still retain a significant amount of data. We then take the average of the 10 pixels in each column to make a 1D strip and plot this on a Counts vs Pixels graph. The low-resolution Hg spectrum is shown as an example in figure 2. This is one that we will be working within the next stage.

4.2 Pixel to Wavelength

Now we must convert the pixel numbers to wavelengths. We begin by using each of the high-resolution Hg lamp exposures to identify the relationship between pixel and wavelength for their expected ranges. We used the known spectra of Hg given in the lab manual [2] with which we identified the emission lines to match the wavelength to the pixel value for as many lines as we could.

There are no Hg spectral lines in the 600-680 nm range so we had to determine these differently. Using equation 1 we solved for p , the pixel to place the line at, by assuming the dispersion is 0.107 nm/pix and the starting wavelength b is 600 nm. Then using the wavelengths of argon spectrum in this range we plotted our lines. This guess is shown in figure 3 and from looking at the spectral shape and the spacing of the lines

we plotted, we concluded that the wavelengths must actually be shifted higher because when we do so the lines align with the peaks.

$$\lambda = ap + b \quad (1)$$

Now that we have identified all the lines, the spectra are shown in figure 4 and the identified lines are marked in red. There is an issue with our data here. Then we repeated the process above for the Hg low-resolution spectra, shown in figure 5.

For unknown reasons, the image with the dark removed was not saved for the first range, so what is shown in figure 4 is the noise data. This doesn't disrupt our identification too much however because some emission lines are still well above the background. Table 3 has the related pixel-wavelength pairs.

Wavelength Range	Pixel	Line Wavelength
360 - 440	261	404.656
	290	407.783
	552	435.833
400 - 480	81	404.656
	111	407.783
	373	435.833
440 - 520	12	435.833}
480 - 560	675	546.074}
520 - 640	307	546.074
	598	576.960
	618	579.066
560 - 640	229	576.960
	249	579.066
600 - 680	108	603.213
	119	604.322
	440	638.471
	470	641.631
640 - 720	615	696.543
	712	706.722

Table 3: By comparing the known spectrum of Hg with ours, we identified an accurate wavelength value for some points on each of our ranges.

Then we calculated the dispersion a in nm/pixel and the starting wavelength b in nm for each spectrum. This gave us a relationship between pixel and wavelength for every range. To do this we assumed the relationship between pixel and wavelength was linear and took the two furthest identified lines apart in each range to use for our calculation. We then solved equation 1 for equation 2, the slope between two points, and equation 3, the starting point, to get a linear fit. If the spectrum only had one line we assumed the dispersion was the same as the range before it and used equation 1 to calculate b using our one point. Using these parameters we are then able to convert a given wavelength to a pixel value to place it at the correct place in the spectrum by solving 1 for p .

$$a = \frac{\lambda_1 - \lambda_2}{p_1 - p_2} \quad (2)$$

$$b = \lambda_1 - p_1 \frac{\lambda_1 - \lambda_2}{p_1 - p_2} \quad (3)$$

5 Results & Analysis

5.1 Sun's Elements

To identify the elements in the Sun we used the known wavelengths of various elements' spectral lines from Larson [3] then converting these wavelengths to pixel values, we plotted them on our Sun spectra for the various ranges shown in figure 6. Our criteria for determining if an absorption line was pronounced enough to detect the element was to test if where the line was placed had 10% less intensity than the max intensity within its error bars to either side of it. The elements that passed these criteria are marked with green lines; the ones that did not are marked with red. The shaded gray areas are the errors on our line placements which are discussed in the next section. Table 4 contains all the accepted elements in each range, their wavelengths, and the differences between the observed and known wavelengths. There is some overlap between the ranges because the ranges overlap in some parts of the spectrum. This is due to having a 'field of view' about 80 nm wide. It is also good confirmation for us that many of the same lines were found in the different images because it helps to reassure us that these are indeed the lines we are looking for. For a full list of all the elements tried see table 6 at the end of the report.

Element	Observed	Table	λ Diff	% Diff
Ca II	396.30	396.85	0.55	0.14
Fe I	404.12	404.58	0.46	0.11
Fe I	405.83	406.36	0.53	0.13
Ca I	422.23	422.67	0.45	0.11
Fe I	425.55	426.05	0.50	0.12
Fe I	426.73	427.18	0.45	0.11
Fe I	432.08	432.58	0.49	0.11
H	433.58	434.05	0.46	0.11
Fe I	437.87	438.36	0.49	0.11
Fe I	404.12	404.58	0.46	0.11
H	409.67	410.17	0.50	0.12
Ca I	422.17	422.67	0.51	0.12
Fe I	425.58	426.05	0.47	0.11
Fe I	426.65	427.18	0.53	0.12
Fe I	432.10	432.58	0.48	0.11
H	433.59	434.05	0.46	0.11
Fe I	437.86	438.36	0.49	0.11
Fe I	440.00	440.48	0.48	0.11
Fe I	441.06	441.51	0.45	0.10
Fe I	437.86	438.36	0.49	0.11
H	485.59	486.13	0.55	0.11
Fe I	495.30	495.76	0.46	0.09
Fe I	526.43	526.96	0.53	0.10
Fe I	532.30	532.81	0.50	0.09
Na I (D2)	588.51	589.00	0.49	0.08
Na I (D2)	588.54	589.00	0.45	0.08
H	655.75	656.28	0.53	0.08

Table 4: These are the identified elements in the Sun in each spectrum range. Starting with the first one and going through the 7th as none were identified in the 8th. From left to right: The predicted element, the observed wavelength, the known wavelength, the difference in nm, and the percent difference. For all of these lines $\sigma_\lambda \approx 0.71$ nm.

5.2 Errors

The two sources of errors throughout this experiment are the accuracy of the micrometer and the accuracy of pixels on our computers. The micrometer is only accurate to a hundredth of a millimeter so we take our uncertainty for that to be $\sigma_m = 0.005$ mm. Similarly, we can only have one pixel of accuracy so we take that uncertainty to be $\sigma_p = 0.5$ pixels. However, we want these uncertainties to be in terms of wavelengths, so using the conversion of the micrometer of 1 mm being equal to 100 nm, we see that $\sigma_{m,\lambda} = 0.5$ nm. Similarly, we know the pixel dispersion for each wavelength range so, with equation 1 we can calculate $\sigma_{p,\lambda}$ for each range which all come out to be approximately 0.505 nm for every range since a is very similar for all ranges. Then we get the total error on wavelength using equation 4 where x equals the number of times we need to account for that error. For the Hg spectrum, x is 1, because we looked at the graphs for the first time; for the Sun spectrum x is 2. Once for using them on the Hg spectrum and again for using them on the Sun spectrum. For Hg $\sigma_\lambda = 0.707$ nm and for the Sun $\sigma_\lambda = 0.866$ nm approximately.

$$\sigma_\lambda = \sqrt{\sigma_{m,\lambda}^2 + x \cdot \sigma_{p,\lambda}^2} \quad (4)$$

6 Discussion

6.1 Sun's Elements

These results are consistent with our uncertainties on the micrometer and the pixels. In figure 6, the gray shading around each line represents the uncertainty, and for each one, the minimum of the absorption line is within these errors. We also checked our errors by going back to the high-resolution Hg spectrum and plotting the emission lines using our a and b parameters; this is shown in figure 7. The red lines are the ones that were used to calculate a and b and the blue lines are the extra lines we had leftover. When we look at these lines with their errors we see that they still include where we originally identified them. This reassures us that our a and b parameters were accurate and we can be confident in the elements we detected.

6.2 Comparison to Models

We also compared our spectrum to empirical stellar templates of A2, F2, G2, K2, and M2 Dwarfs with zero metallicity. The different classes of stars are defined by their temperatures and therefore they differ in the color of light they emit. This in turn affects the absorption lines that we see because a hot star may contain elements that absorb higher energy wavelengths, unlike what we saw for the Sun, where the absorption lines became less pronounced as wavelength increased. Table 5 lays out these characteristics [4].

Type	Temperature	Color
A	7,500–10,000 K	white
F	6,000–7,500 K	yellow white
G	5,200–6,000 K	yellow
K	3,700–5,200 K	light orange
M	2,400–3,700 K	orange red

Table 5: Classification of Stars. The letter is related to the temperature of the star and therefore the part of the spectrum that it emits in. The Sun is a type G2 star and falls in the range with a surface temperature of 5,800 K.

To do the comparison, we overlayed spectra from Kesseli et al. [5] of these classes of stars over two wavelength ranges: 376–451 nm and 552–626 nm. To do this we normalized both our spectrum and Kesseli's by dividing them by their median and then shifting Kesseli's spectrum up so that they weren't right on top of each other. With this, we can compare the shapes of the spectra to determine what type of star the Sun is. Figure 8 shows all these fits.

From this, we can do a fit-by-eye to see that for both ranges the G2 dwarf fits our measurements the best. This is what we expect, as the Sun is a G2 dwarf. We also notice that the fits for F and K don't look

very different either. This makes sense because F and K are the classifications adjacent to G, so they may have some overlap in their emissions. Meanwhile, the temperature difference between the Sun and a type A star is larger and the spectra don't resemble each other at all.

In future work, we could be able to use our pixel conversions to identify what elements are common in the other types of stars by repeating the process we did to identify the Sun's elements.

We could also use the G2 spectrum to scale our spectrum so that the normalized intensities overlap. This is useful because this required conversion factor is related to the scattering of blue light in the atmosphere. Although we wanted to observe the light directly from the sun, the light of course scatters throughout the atmosphere so some of this light added to the intensity of our spectrum. By fitting our spectrum with the G2 spectrum we can have an estimate of how large this effect was.

6.3 Black Body Spectrum

The Sun is a black body so we should be able to fit our low-resolution spectrum to equation 5 with h the Planck constant, c the speed of light, and k the Boltzmann constant. Figure 9 shows this spectrum and we plot the same spectral lines as in the high-resolution plots, but with dismissed accuracy, we can see that these don't line up as well. Using the parameters a and b for the low-resolution spectrum we input a wavelength for each pixel and left A the amplitude and T the temperature as free parameters. Figure 10 shows the fit with $A = 2.53 \times 10^{10} \pm 2.96 \times 10^{18}$ and $T = 9.86 \times 10^3 \pm 5.54 \times 10^4$.

$$f(\nu, A, T) = \frac{2\pi h \nu^3}{c^2} \frac{A}{e^{\frac{h\nu}{kT}} - 1} \quad (5)$$

The value our fit found for temperature is far off from the known value of $5,772K$ (Phillips [6]), but with massive errors, we do cover this temperature. This is still by no means a good fit, but it is interesting that we found something 'close' to the setup that we had. Even the shape of the fit, although lacking in precision around the edges, raises and falls with our data, and even peaks at the correct point.

A reason for this mismatch could be that we took no flats for this experiment and the edge of the CCD is less sensitive than the center so this discrepancy was never corrected for. This allowed us to get an image of the correct spectrum, but the counts around the edges appear to be much lower than they should be, and therefore we aren't measuring an accurate intensity.

Future work for the black body could be retaking data and using flats in our measurements. Another possibility could be to make a complete spectrum using the high-resolution spectra. This would be challenging because the intensity for each range is different so there would need to be some kind of normalization to make this work. This could work better than using the low-resolution spectrum though because if the lower intensity on the side of the CCD really is the problem then having multiple overlapping ranges like we have may be able to lessen this issue.

7 Acknowledgements

I would like to acknowledge my instructor Olivier Hervet, my teaching assistant Miguel Escobar Godoy, and my lab partners Atirath Dhara and JT Earwicker for their support on this project.

Element	Accepted	Observed	Table	λ Diff	% Diff
Ca II	X	—	393.37	—	—
Al I	X	—	394.40	—	—
Al I	X	—	396.15	—	—
Ca II	0	396.30	396.85	0.55	0.14
Fe I	0	404.12	404.58	0.46	0.11
Fe I	0	405.83	406.36	0.53	0.13
Fe I	X	—	407.17	—	—
Sr II	X	—	407.77	—	—
H	X	—	410.17	—	—
Fe I	X	—	413.21	—	—
Fe I	X	—	414.39	—	—
Mg I	X	—	416.73	—	—
Fe I	X	—	420.20	—	—
Ca I	0	422.23	422.67	0.45	0.11
Fe I	X	—	423.59	—	—
Fe I	X	—	425.01	—	—
Fe I	X	—	425.08	—	—
Cr I	X	—	425.43	—	—
Fe I	0	425.55	426.05	0.50	0.12
Fe I	0	426.73	427.18	0.45	0.11
Fe I	0	432.08	432.58	0.49	0.11
H	0	433.58	434.05	0.46	0.11
Fe I	0	437.87	438.36	0.49	0.11
Fe I	X	—	440.48	—	—
Fe I	X	—	441.51	—	—
Fe I	X	—	452.86	—	—
Ba II	X	—	455.40	—	—
Al I	X	—	396.15	—	—
Ca II	X	—	396.85	—	—
Fe I	0	404.12	404.58	0.46	0.11
Fe I	X	—	406.36	—	—
Fe I	X	—	407.17	—	—
Sr II	X	—	407.77	—	—
H	0	409.67	410.17	0.50	0.12
Fe I	X	—	413.21	—	—
Fe I	X	—	414.39	—	—
Mg I	X	—	416.73	—	—
Fe I	X	—	420.20	—	—
Ca I	0	422.17	422.67	0.51	0.12
Fe I	X	—	423.59	—	—
Fe I	X	—	425.01	—	—
Fe I	X	—	425.08	—	—
Cr I	X	—	425.43	—	—
Fe I	0	425.58	426.05	0.47	0.11
Fe I	0	426.65	427.18	0.53	0.12
Fe I	0	432.10	432.58	0.48	0.11
H	0	433.59	434.05	0.46	0.11
Fe I	0	437.86	438.36	0.49	0.11
Fe I	0	440.00	440.48	0.48	0.11
Fe I	0	441.06	441.51	0.45	0.10
Fe I	X	—	452.86	—	—
Ba II	X	—	455.40	—	—
Mg I	X	—	470.30	—	—

Element	Accepted	Observed	Table	σ_λ	λ Diff	% Diff
Fe I	0	437.86	438.36	0.49	0.11	
Fe I	X	—	440.48	—	—	
Fe I	X	—	441.51	—	—	
Fe I	X	—	452.86	—	—	
Ba II	X	—	455.40	—	—	
Mg I	X	—	470.30	—	—	
H	0	485.59	486.13	0.55	0.11	
Fe I	X	—	489.15	—	—	
Fe I	X	—	492.05	—	—	
Fe I	0	495.30	495.76	0.46	0.09	
Mg I	X	—	516.73	—	—	
Mg I	X	—	517.27	—	—	
Mg I	X	—	518.36	—	—	
Fe I	X	—	525.02	—	—	
Fe I	0	526.43	526.96	0.53	0.10	
Fe I	0	532.30	532.81	0.50	0.09	
Mg I	X	—	552.84	—	—	
Mg I	X	—	516.73	—	—	
Mg I	X	—	517.27	—	—	
Mg I	X	—	518.36	—	—	
Fe I	X	—	525.02	—	—	
Fe I	X	—	526.96	—	—	
Fe I	X	—	532.81	—	—	
Mg I	X	—	552.84	—	—	
Na I (D2)	0	588.51	589.00	0.49	0.08	
Na I (D1)	X	—	589.59	—	—	
Na I (D2)	0	588.54	589.00	0.45	0.08	
Na I (D1)	X	—	589.59	—	—	
Ca I	X	—	610.27	—	—	
Ca I	X	—	612.22	—	—	
Ca O	X	—	616.22	—	—	
Fe I	X	—	630.25	—	—	
Ca I	X	—	610.27	—	—	
Ca I	X	—	612.22	—	—	
Ca O	X	—	616.22	—	—	
Fe I	X	—	630.25	—	—	
H	0	655.75	656.28	0.53	0.08	
H	X	—	656.28	—	—	

Table 6: All expected elements in the Sun and whether we accepted them or not.

References

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