Temperature of the photosphere of the Sun from solar spectra

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We recorded solar spectra using an OceanOptics HR2000 spectrometer to determine how well the Sun approximates a blackbody by using our experimental peak wavelength to calculate the surface temperature and compare this with the effective temperature. From these spectra, we located the Fraunhofer lines of the Sun to ascertain the composition of the photosphere, which we found to be in agreement with known values. We took spectra at various angles measured from the horizon in order to observe the effects of atmospheric interference.

I. INTRODUCTION

Interference on astronomical observations from the Earth's atmosphere, weather, rotation, orbit, and position in the ecliptic has been studied in depth from solar spectra. The properties measured led to advancement in the fields of optics, nuclear physics, thermodynamics, and chemistry which produced discoveries that developed quantum theory. The overall shape of the intensity of radiation emitted by the Sun contained sharp, dark spectral lines within its continuous spectrum. These lines were discovered to represent the absorption by certain elements in the Sun's photosphere or outer layers. [1] Over the decades, advancements in spectroscopy have yielded more accurate measurements of the solar spectrum.

Our recording of solar spectra sought to replicate previous and current measurements taken in order to compare the solar spectrum with that of a black-body, study the temperature and composition of the photosphere, and obtain calibration data for the measured intensity and wavelengths by our OceanOptics spectrometer. These observations verified Max Planck's original discovery in 1900 of Planck's Law which marked the advent of quantum mechanics, and provided a profound demonstration of the quantum relationship between energy and the frequency of electromagnetic waves that classical descriptions failed to explain. [2]

We used an Ocean Optics spectrometer with a 350-800 nm range and fiber optic cable to record solar spectra at various angles. We used a calibration device to calibrate our measurements and compare our solar spectra to that of an idealized blackbody. We then used Wien's displacement law to determine the temperature of the Sun's photosphere. We compared this temperature to the effective temperature, the temperature that a blackbody would emit with the same amount of electromagnetic radiation, in order to determine how our measured emissivity compared to that of a blackbody.

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II. THEORETICAL BACKGROUND

A star typically fuses isotopes of hydrogen in its core and emits photons that have increasingly longer wavelengths as the radiation diffuses outward. After the radiation passes through the hot, opaque gaseous layer producing a continuous spectra, the cooler layer of gas called the atmosphere yields absorption lines in this spectra. [1] As the photons pass through this layer they are absorbed by the atoms of the gas at the same wavelength they require to gain an energy level, providing absorption lines in the spectra that indicate the chemical composition of the photosphere. [1] These lines are known as Fraunhofer lines, observed by Joseph von Fraunhofer in 1814 in the Sun's optical spectrum. [1] Modern observations can detect thousands of these lines.

A. Atmospheric Interference

The light that passes through the Earth's atmosphere encounters many obstacles. The Earth's atmosphere is highly composed of Ozone and Nitrogen, so these absorption lines are present when making ground based spectral observations. [1] Halogens cause emission lines in spectra when recording data from the Earth's surface due to the Halogen lamps commonly used in urban areas. [1] The humidity, dust, and pollution levels at the location of observation also effect the spectrum.

Another factor impacting the photons is a measurable redshift affect that occurs due to the rotational and orbital motion of the Earth. As the photons are collected and travel down the observational pathway, the earth rotates and experiences a velocity, so the photons are redshifted during this time. [1] Additionally, there is the effect referred to as aberration or scattering where photons are scattered by molecules they encounter as they traverse through the atmosphere which produces a smearing or blurring effect. This effect is greatest when collecting data at zero degrees measured from the horizon and is least when taken pointing at the zenith or 90 degrees from the horizon. This is an advantage of collecting light at certain wavelength or using space and atmospheric telescopes as opposed to ground based telescopes. [1]

Many of these effects are negligible when studying solar spectra, although they are still present. However, Rayleigh scattering has a measurable impact on solar spectra taken from the Earth. Rayleigh scattering is an effect that occurs due to the electric polarizability of particles that are much smaller than the wavelength of the light or other radiation. [1] The particles' charges are acted on by the oscillating electric field of the light wave and become a small radiating dipole we see as scattered light. [1] In the Earth's atmosphere, Rayleigh scattering of sunlight is the cause of the blue hue of the sky during the day and red hues when the Sun is lower. [1]

B. Planck's Law and Black-body Radiation

The Sun's spectra is a fairly good approximation of a blackbody. A blackbody is an idealized opaque, non-reflective body, meaning one that completely absorbs all radiation that falls upon it at every frequency ν, that is in thermodynamic equilibrium at temperature T with its surroundings. This body emits thermal electromagnetic radiation as a specific spectrum of wavelengths that is inversely dependent only on the body's temperature, which is assumed to be uniform and constant.

Emissivity characterizes an objects ability to emit energy as thermal radiation, and is represented by the ratio of thermal radiation emitted to the radiation emitted by an ideal opaque surface with the same temperature. This value is found from

$$F = \sigma T^4 \tag{1}$$

known as the Stefan-Boltzmann law, where F is the flux, σ is the Stefan-Boltzmann constant, and T is the temperature of the blackbody in Kelvin. Since a black body emits all energy as thermal radiation, a perfect blackbody has an emissivity of 1.

The relationship between spectral density of electromagnetic radiation to temperature is known as Planck's law, and assumes that there is not net flow of matter or energy between the body and environment. However, spontaneous emission of thermal radiation by an object, such as stars which are not in thermal equilibrium with their surroundings, can be appropriately approximated as black-body radiation. [1]

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1} \tag{2}$$

where k_B is the Boltzmann constant and h is the Planck constant. This formula has various forms and is presented here in the relevant wavelength form.

Max Planck's derivation of this formula was done by assuming that a hypothetical electrically charged oscillator in a cavity of black-body radiation could change only its energy in increments of E that were proportional to the frequency ν of the associated electromagnetic wave. [2]

Lord Rayleigh and Sir James Jeans attempted to classically define, via the equipartition theorem, Gustav Kirchhoff's law of thermal radiation characterizing a black body's emissive power, yielding the inconsistent Rayleigh-Jeans law. [3] This classical view predicted that the total radiation intensity of a perfect blackbody would be infinite, and is aptly referred to as the ultraviolet catastrophe. Planck's discovery, by assuming quantized emission of radiation, resolved this issue.

Classical thermodynamics depicts some of the properties of the Planck distribution. Wien's Law is a direct consequence of Planck's radiation law, although it was discovered prior to the development of Planck's law. Wien's displacement law states a black-body radiation curve will peak at a wavelength that is inversely proportional to temperature. This relationship is given by

$$\lambda_{peak} = \frac{b}{T}, \tag{3}$$

where b = $2.897771955 \times 10^{-3} m \cdot$ K is called Wien's displacement constant, and T is the absolute temperature. [1]

The quantum theoretical explanation of Planck's law describes the radiation as a photon gas in thermodynamic equilibrium. The photons are created and destroyed to achieve the correct energies to occupy the cavity with the Planck distribution. Unlike material gasses, the photon gas's internal energy density, which determines the pressure, is only related to the temperature. Planck's relationship is governed by the Bose-Einstein distribution, which describes how a collection of non-interacting, indistinguishable particles in thermodynamic equilibrium can occupy a set of available discrete energy states. [4] At low temperatures, unlike fermions, bosons can occupy the same quantum state.

III. EXPERIMENTAL PROCEDURE

First, we connected our OceanOptics HR2000 spectrometer, with a spectral range of 350-800 nanometers, via DNC to a calibration source of specified wavelengths in order to determine a function of correction values for our measured wavelengths. We then connected our spectrometer using a USB to our computer and used SpectraSuite software to save this data set. Next, we disconnected the calibration source and connected a fiber optic cable to our spectrometer.

We then took our experimental setup outdoors, and mounted our fiber optic cable using an adjustable clamp. We then recorded solar spectra at various angles measured from the horizon using SpectraSuite software, making sure to only take data when no clouds were blocking the Sun from our optical fiber's path.

We utilized a provided set of correction values taken with our spectrometer using a spectral lamp as a source to adjust our recorded intensities, which were dependent upon wavelength. We used Python to analyze and apply fits to our data. Finally, we determined the peak spectral wavelength to deduce the temperature of the photosphere from the spectral composition of the solar atmosphere and compared this distribution to a blackbody distribution.

IV. DATA

The weather on the day of our experiment was mostly sunny with a small amount of infrequent clouds. We only recorded spectra when the Sun was not blocked by any clouds. The humidity was 50% and the temperature was 89 degrees Fahrenheit. We began recording spectra at 3:53 pm. The visibility was 10 mi and the air quality index was 39.

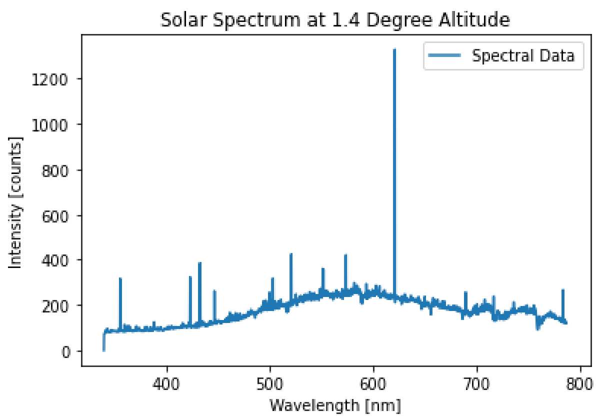

FIG. 1. Solar Spectrum at an Altitude of 1.4 Degrees

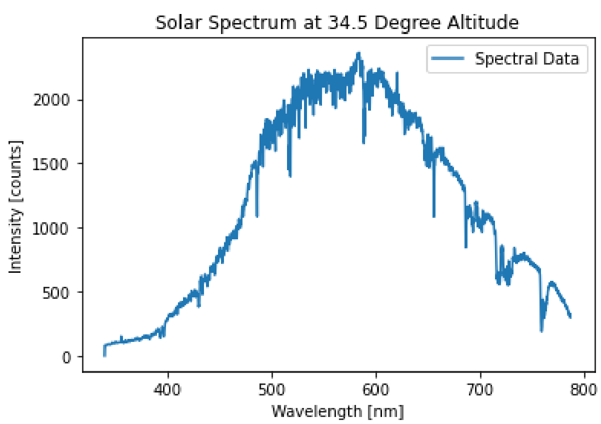

FIG. 2. Solar Spectrum at an Altitude of 34.5 Degrees

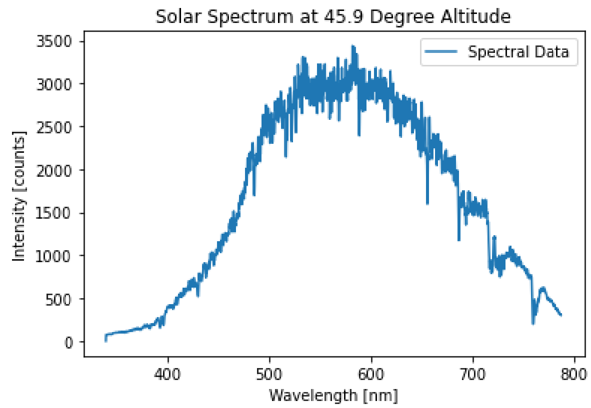

FIG. 3. Solar Spectrum at an Altitude of 45.9 Degrees

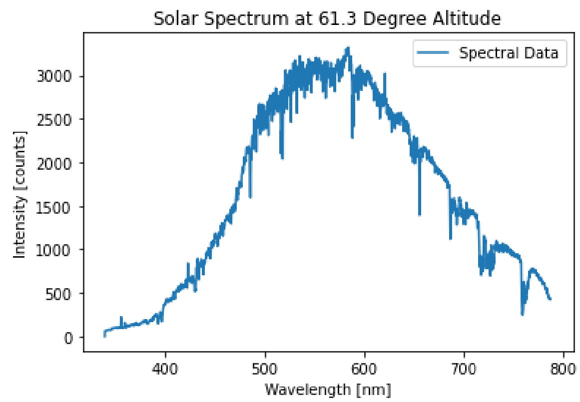

FIG. 4. Solar Spectrum at an Altitude of 61.3 Degrees

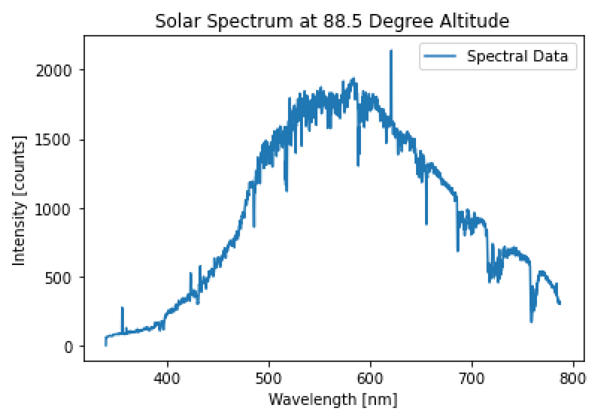

FIG. 5. Solar Spectrum at an Altitude of 88.5 Degrees

V. ANALYSIS

From the calibration data, we found a 0.26% increase in our recorded wavelength values.

TABLE I. Photosphere Temperature from Solar Spectrum

Altitude [Degrees]	λ_{peak} [nm]	Temperature [K]
1.4	621.01 ± 1.61	4666.2 ± 12.132
34.5	583.88 ± 1.51	4963.0 ± 12.904
45.9	581.92 ± 1.51	4979.7 ± 12.947
61.3	583.88 ± 1.51	4963.0 ± 12.904
88.5	621.01 ± 1.61	4666.2 ± 12.132

We also recorded a data set by positioning our fiber optic cable such that the spectrum was reading the highest intensity. This was achieved by aiming the cable directly at the Sun. λ_{peak} for this spectrum was 489.21 $\pm$1.27 nm and the temperature from Wien's displacement law was 5923.4 $\pm$15.4 K.

We compared our recordings of the solar spectra and its properties with that of an ideal blackbody's distribution.

VI. CONCLUSION

We found a temperature for the Sun's photosphere of 4963.0 ± 12.132 K and a variation from the effective temperature 5777 K of 14.09%.

We were able to achieve the goal of our experiment of taking solar spectra at various altitudes in order to make comparisons with a blackbody spectrum, estimate the temperature and composition of the photosphere, and perceive the interference from the Earth's atmosphere on spectral observations. Our Fraunhofer lines were similar to the known composition of the photosphere as well. We observed that although not an ideal body, the solar spectrum was a good approximation of a blackbody.

Further analysis in this experiment could be made using our data to estimate Avogadro's number following analysis of Rayleigh scattering. Future replications should be sure to include data taken with the lower resolution spectrometer to make more accurate comparisons with an ideal blackbody spectrum.

Issues arose in our experiment when taking data due to occasional clouds interrupting our recordings. We also did not have an instrument which could accurately measure the altitude. A small impact on the measurements taken by our spectrometer also resulted due to measuring our calibration data indoors where the temperature was near 70°F but recording our spectra in 89°F weather outdoors. [5] The humidity and air quality index on a given day also impacts the spectral data taken.

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