# Determining the Sun's Surface Temperature With iPhone

P. D. Mullen and C. N. Woods
*Department of Physics and Astronomy,*
*University of Georgia, Athens, Georgia 30602*

(Dated: 8 December 2015)

The principles behind blackbody radiation make it possible for one to measure the surface temperature of many objects based upon the distribution of emission intensity per wavelength. These same principles can be even applied to measure the surface temperature of objects millions of miles away – for instance, our sun at around 93 million miles from Earth. Herein, we apply the fundamental physics behind blackbody radiation theory to measure the surface temperature of the sun, which is known to be 5778 K, using a homemade spectrophotometer with optical components designed from everyday objects including the Complementary Metal-Oxide-Semiconductor (CMOS) type detector of an iPhone 5S, Legos, electrical tape, and a diffraction grating with a fixed budget. Using this device, we performed measurements of the sun from Athens, GA, in conjunction with the webpage application, *Spectral Workbench*. As we will discuss, several key considerations must be made regarding the possible sources of error associated with these measurements. Firstly, calibration of the iPhone spectrophotometer is required to minimize error from the instrument itself: 1) we calibrate via a known fluorescent source with characteristic mercury emission features to discern which wavelengths of sunlight are associated with which intensities and 2) utilize two unique techniques of calibration (a. directing spectrophotometer directly at sunlight, b. directing spectrophotometer at a reflective surface to reduce intensity of incident light) in order to minimize effects of non-linearity in detection of the CCD within the iPhone. In addition to errors associated with the instrument itself, we must also consider how atmospheric conditions may affect the spectrum we generate: 1) atmospheric molecules absorbing solar radiation ($O_2$ and $H_2O$), 2) times of measurement (intensity of solar radiation), and 3) the weather conditions (cloudy vs. sunny) that may also affect the generated spectrum. At the conclusion of our construction, experiment, and data analysis, we determine the surface temperature of the sun to be $T = 6000 \pm 300$ K. The true surface temperature falls within these error bars and the percent error between the known temperature and our best estimate is a mere 3.8%.

## I. Introduction: The iPhone Spectrophotometer and the Photosphere of the Sun

93 millions away from Earth, the Sun undergoes nuclear fusion at its core and reaches upwards of 15 million K. As this thermal energy radiates from the star's core to surface, or the photosphere, the temperature falls to 5778 K. It is in the photosphere that the sun's radiation is detected as sunlight. In this work, we test the fundamental physics (i.e. a blackbody radiation model) of the photosphere by designing a simple yet intuitive spectrophotometer using an iPhone, diffraction grating, and a filter/shield to observe the emission of the Sun in efforts to measure its surface temperature. Such an instrument is idealized in Figure 1. Discussions pertaining to the construction and components of this device are later addressed in this report. Many concerns revolving around making measurements with this apparatus and the subsequent application of models are addressed in this report; for instance: 1) the careful calibration of the apparatus, 2) the times and locations for measurements of the sun's emission, 3) fitting the observed data of a limited range of wavelengths to a broader scale spectrum using a powerful Python fitting program, and 4) accounting for sources of error associated with the optical components and measurements made in this experiment.

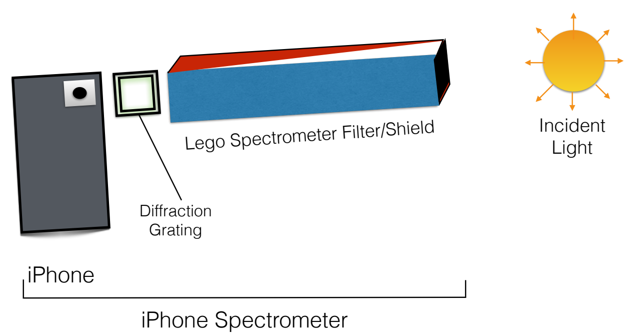


FIG. 1: Schematic of the iPhone Spectrophotometer. The components shown above include the iPhone, diffraction grating, and the Lego Spectrophotometer Tube. Not shown are the electrical tape supports.

## II. Theory: Blackbody Radiation

When heated, many bodies give off radiation. The frequency of radiation increases as the temperature of the body increases. We can estimate the emission spectrum of many radiating objects by approximating/considering them to be blackbodies. A black body is an ideal body that absorbs and emits all frequencies and whose radi-

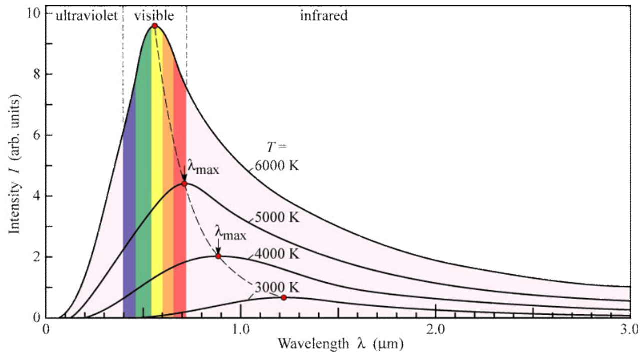


FIG. 2: Blackbody radiation diagram for multiple blackbody temperatures, T. $\lambda_{max}$ values are given and are precisely the maximum intensity for a given radiation curve. This figure was obtained from http://quantumfreak.com/wp-content/uploads/2008/09/black-body-radiation-curves.png

ation is modeled exactly by the Planck distribution as derived by Max Planck in 1900. To be explicit, in this work, the photosphere of the sun is modeled as a blackbody. Blackbody radiation perplexed physicists prior to the beginning of the 20th century as their derivations incorporating classical physics reported that intensity diverged to infinity at the ultraviolet wavelengths (i.e. the ultraviolet catastrophe). In 1900, Max Planck incorporated his idea of quantized energy and was able to derive what is presently the most commonly used distribution for blackbody radiation and opened the door to the field of quantum physics. This distribution is given as

$$\rho_\lambda(T)d\lambda = \frac{8\pi hc}{\lambda^5}\frac{d\lambda}{e^{\frac{hc}{\lambda k_B T}} - 1} \tag{1}$$

This distribution is plotted in Figure (2) for several different objects of different surface temperatures, T. Also, Figure (2) depicts that the radiation corresponds to all wavelengths of emitted light. For reasons that will later be discussed, for temperatures around 5000-7000 K, the $\lambda_{max}$ falls within the visible portion of the emission spectrum. One can explictly find the maximum wavelength of the blackbody radiation by differentiating equation (1) and setting it equal to zero. Here, we can determine that the $\lambda_{max}$ associated with the emission spectrum is given as

$$\lambda_{max}T = 2.90 \times 10^{-3}\ m \cdot K \tag{2}$$

Thus, if we know $\lambda_{max}$, we can determine the surface temperature of the radiating object from equation (2). This is how we will measure the surface temperature of the sun. As discussed in later sections, we will attempt to find $\lambda_{max}$ through a series of observations with the iPhone spectrophotometer, apply a powerful Python fitting tool to extract the entire spectrum and find the wavelength, $\lambda_{max}$, which maximizes the extrapolated blackbody radiation curve.

FIG. 3: Execution of iPhone Spectrophotometer Construction.

## III. The Apparatus

### A. Construction

We will be using the rear camera of an iPhone 5S as the detecting device in our experimental set up. The camera is a custom Sony Exmor RS device, which is a Complementary Metal-Oxide-Semiconductor (CMOS) type detector. The iPhone is well suited as a ready to use spectroscopic device due to the presence of webpage applications which can be used to extract/generate observational spectra. As shown, in Figure 1, to build the idealized spectrophotometer, the main optical devices required were an iPhone 5s, a diffraction grating, and a Lego Spectrophotometer Filter/Shield. This constructed Lego filter/shield allows for a channel of light from a desired source, in this case, the sun (photosphere), to be directed to our detector while hopefully limiting as much external interference as possible. To this filter/shield, a diffraction grating is attached. The diffraction grating will separate out various wavelengths of the incoming light so that the iPhone 5S camera can generate a spectral picture in which the webpage application, *Spectral Workbench*, can analyze.

Until now, we have presented the idealized spectrophotometer and its components and their purpose in the measuring the surface temperature of the Sun. However, the actual construction of the device required special additions to secure such devices. Therefore, in addition to the aforementioned, the spectrophotometer also required an iPhone 5s case, black tape, super glue, and a drill for assembly. First, holes were drilled through the center of Lego pieces and then the pieces were attached so that the hole went all the way through the construction

– thus generating the filter/shield. Over the hole on the case, the diffraction grating was taped so that only a thin slit of grating was visible. The grating was taped so that the lines of the grating were perpendicular to the length of the case. The tape was placed parallel to the lines of the grating. The hole on the bottom side of the Lego construction was also taped over so that there was only about 1 mm of space between the tape. The Lego construction was then glued over the diffraction grating taped to the phone case so that both slits were lined up. Additional tape was used to secure the Lego construction in place while the glue set. Black was used for all parts of the construction so that effects of scattering from the construction were limited to ensure as pure of a spectrum as possible. All edges were also taped so that no ambient light could get into the optical piece. The only materials purchased were the tape, glue and phone case. A picture of our execution of constructing the iPhone spectrophotometer is given in Figure 3. The total cost was $14.67. For itemized expenditures, see the cost section of this report.

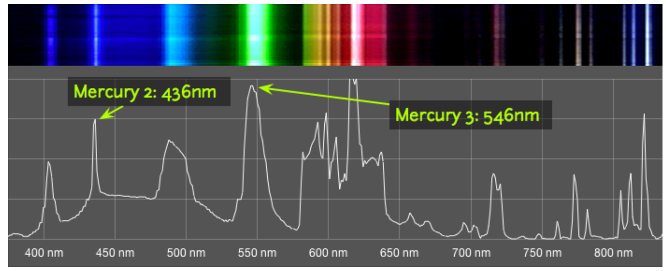


FIG. 4: Calibration Technique: Identification of Mercury Peaks in Fluorescent light spectrum. This figure was obtained from https://publiclab.org/wiki/spectral-workbench-calibration

FIG. 5: Raw Data: Spectral Image Prior to Processing

### B. Calibration

It would be useless to use our device without correctly calibrating it for spectral response. To this end, we required for calibration to take a leading role in this project. The CCD cameras in typical cell phones generally have a wavelength response in the range of 350 - 1000 nm. This means that our cell phone detector will be able to detect the peak solar wavelength as it should fall in this range. The CCD cameras also show non-linear responses in regards to intensity. To correct for non-linearity in the intensity measurements, we varied the intensity of the light in our observations to detect and correct for non-linearity in the intensity response of the CCD detectors. To be more specific, two techniques were applied in observations: the first was generating a “dark spectra”, obtained from fluorescent source in which a plastic covering lowered the intensity of the source. The second was a “bright spectra”, obtained by removing the plastic covering and using the unblocked intensity of the light. By comparing the “bright spectra” analysis to the “dark spectra” analysis, we minimize the effects of the intensity response of the CCD detectors and implement such differences in the two methods into our uncertainty in observation. No matter which technique is applied to minimize the effects of the non-linear response of the CCD camera, the generated spectral image remains to be calibrated (i.e. the device must be calibrated so that the wavelengths associated with the intensities of the source can be determined). In order to obtain the wavelengths of the spectrum, the site uses the spectrum taken with the device from a fluorescent light bulb to do this calibration. Two peaks in the fluorescent bulb spectrum are identified by the user which are typical of the spectrum. These peaks correspond to mercury emission features from the fluorescent light source as seen in Figure 4 which was gathered from the *Spectral Workbench* calibration instructions.

### C. Detection Methodology and Observational Challenges

For the purposes of measuring the solar spectrum, we used a fairly simple methodology. To obtain the spectra, the tube of the device was directed at the light source in question and then the angle was changed until a spectrum appeared on the image. A picture was then taken. There was generally no diffraction pattern when the device was directed straight at the source. The diffraction pattern is due to reflection of the source light inside the tube of the spectrophotometer. The resulting image gives the raw spectral data to be implemented into the *Spectral Workbench* application. An example of such a raw image is given in Figure 5. The image must cropped so that only the spectrum was present and oriented so that the violet region was on the left and the red region was on the right. After calibration (as mentioned in the previous section), the capabilities of the Spectral Workbench site were then used to obtain a spectrum from the colored image. These measurements were taken over the course of one day from 10 a.m. to 4 p.m. once an hour to correct for atmospheric changes and intensity changes throughout the day. The measurements were made in Athens, GA, on a clear sunny day. To give a qualitative and representative picture of these conditions, Figure 6 depicts the sky on observation day as viewed atop UGA’s journalism building. As viewed in the picture, we chose a day that would hopefully eliminate any at-

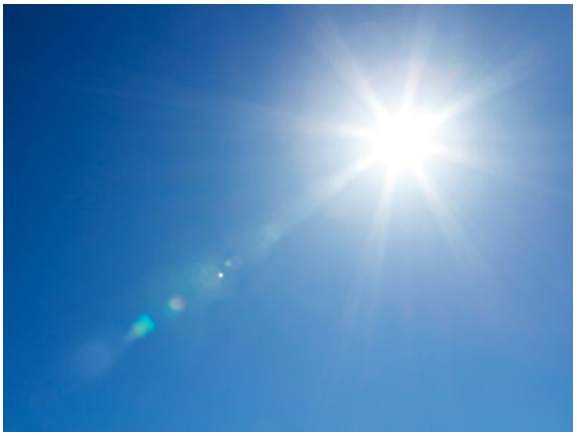

FIG. 6: Observation Day Conditions: Viewed Atop UGA's Journalism Building

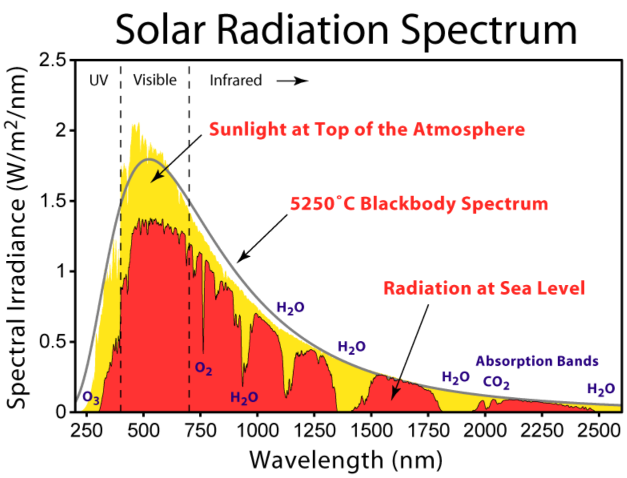


FIG. 7: Peculiarities of observed radiation curves due to absorbance of radiation by atmospheric molecules $O_2$, $H_2O$, and $CO_2$ and dependence of elevation at which measurement is taken. Picture obtained from Dr. Yiping Zhao's Chapter 2 UGA PHYS 3330 Lecture Notes.

mospheric peculiarities of the region that could hinder our efforts. However, more generally, it is well known that many molecules within Earth's atmosphere absorb light thus leading to unusual features in the blackbody radiation curve. For instance, Figure 7 depicts the absorbance of radiation by $O_2$, $H_2O$, and $CO_2$ in Earth's atmosphere. Further, the figure shows how even the elevation at which the measurement is taken could affect the observed radiation curve.

## IV. Model Fitting – Python Routines and Statistical Analysis

In reference to Figure 2, it is imperative that one understands that the iPhone spectrophotometer is only capable of observing electromagnetic radiation in the visible part of the emission spectrum. A series of data points can be extracted from the *Spectral Workbench* as discussed in the detection methodology section. In an effort to determine the $\lambda_{max}$ of the emission spectrum and to model the curve with a blackbody radiation distribution, we apply a powerful Python program, named ***Helios***, that takes the observational data from the iPhone spectrophotometer uses it to fit to the model distribution as given in equation (1). From here, we can deduce the temperature associated with the emitting object directly, **or** we can find the maximum wavelength associated with our extrapolated distribution and find the corresponding surface temperature using equation (2). The python fitting routine is robust and fast. A series of 14 observational data sets are analyzed in a fraction of seconds while analyzing quantitative statistics such as the chi-squared value, reduced chi-squared value, degrees of freedom, p-values, percent errors, and percent differences all while tracking the errors associated with the measurements and making 28 figures corresponding to fitting each set of data and giving residual analysis. Thus, by accounting for error and applying such powerful modeling tools, we can give the the sun's surface temperature, with uncertainty, and statistical parameters supporting our results.

## V. Results and Discussion

***Helios*** was applied to 14 different sets of observational data spanning an observation period from 10 a.m. and 4 p.m. – 7 using our defined "bright spectra" and 7 using "dark spectra". The output of the streamlined program set is 28 figures comprised of model fits and residual analysis. We will focus on 4 of these graphs. Figures 8 depicts the observational data (green points) and the corresponding fit to a blackbody radiation distribution (red curve) utilizing the "bright spectra" data. It is very important to note that each of these spectra have been normalized to the intensity occurring at $\lambda_{max}$. This has been performed for ease of comparing spectra and is often a customary mode of analysis for emission spectra. Qualitatively, we can see that there is excellent agreement between the theory and observations. More powerfully, statistical analyses also reveal an excellent fit with a reduced chi-squared value of 0.004549 and a p-value very close to ˜1.0. We see further that the the theoretical curve mostly falls within the error bars of the intensity measurements. These error bars were determined by considering the change in intensities of the same wavelength for spectra taken in rapid succession and is equal to 0.05. From the fits and data, a $\lambda_{max}$ value of 493 $\pm$ 2 nm was found which corresponds to a temperature of 5880 $\pm$ 20 K via Equation 2. The origination of uncertainty comes from the 2 nm uncertainty in identifying the location of the mercury emission peak in the calibration procedure. Figure 9 gives a residual analysis for this fit. We see that the residuals float around 0.00 but there is a particularly interesting feature occurring around ˜640 nm. Although our main goal for this work was to identify the sun's surface temperature, we are very excited by this peak as we

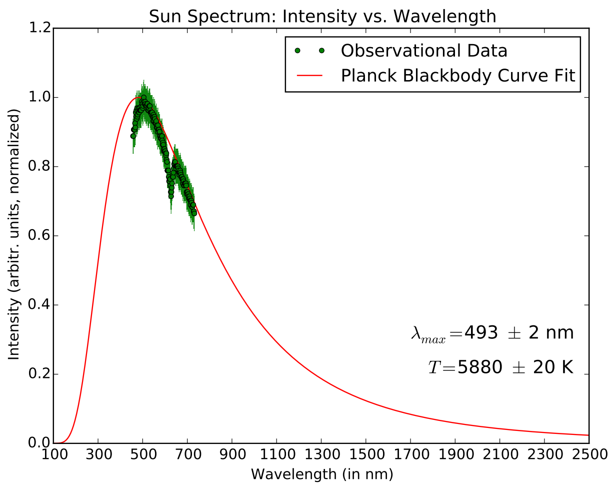


FIG. 8: Model Fit and Observational Data from Bright Calibration Method.

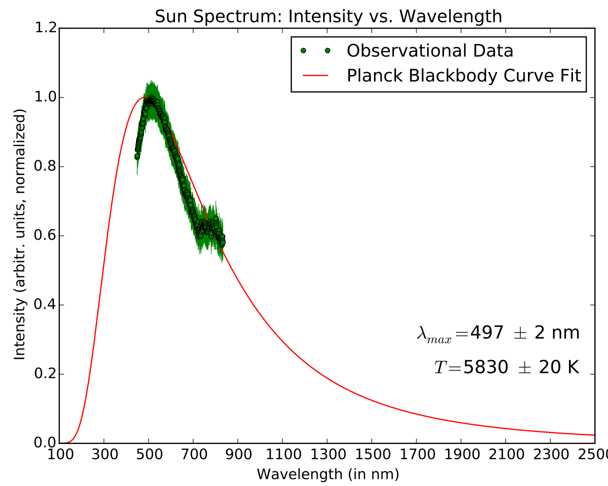


FIG. 10: Model Fit and Observational Data from "Dark" Calibration Method.

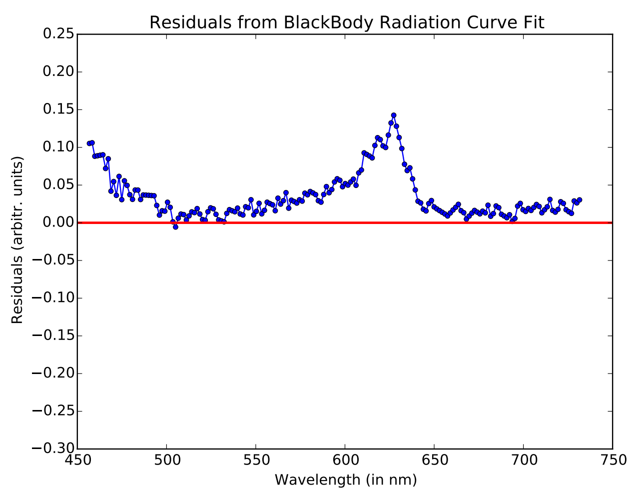


FIG. 9: Residual Analysis Bright Calibration Method.

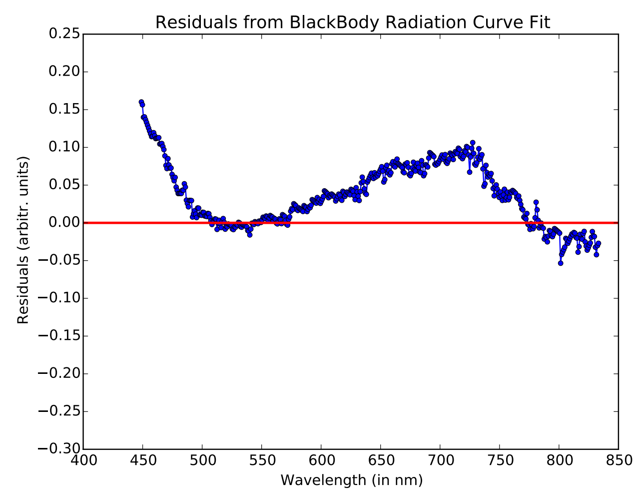


FIG. 11: Model Fit and Observational Data from "Dark" Calibration Method.

know this is around the location for atmospheric $O_2$ vibrational absorption (630 nm and 690 nm) as depicted in Figure 7 which clearly explains the dip in intensities and increase in the residuals about this wavelength.

Figure 10 depicts the observational data (again, green) and the corresponding fit to the blackbody radiation distribution function (red curve). Again, we see excellent qualitative agreement and an excellent chi-squared value of 0.004321 an a p-value again very close to ~1.0. From the fits an observational data, a $\lambda_{max}$ value of 497 $\pm$ 2 nm was determined which gives a temperature of 5830 $\pm$ 20 K. Figure 11 gives the residual analysis which floats around 0.00 but again shows the very interesting (but less distinct) peak that we attribute to $O_2$ absorption in Earth's atmosphere. Utilizing the results from every set of observational data, "bright spectra" **and** "dark spectra", **Helios** averages each temperature while considering all uncertainties so that we can report our best estimate and uncertainty for the sun's temperature which we find to be $T = 6000 \pm 300$ K. The true value of the photosphere's temperature is 5778 K. Therefore, we feel successful in reaching our project goal as we have achieved a 3.8% percent error in this known value while also having been able to identify key absorption features in Earth's atmosphere.

## VI. Sources of Error

As this is a rather simple device, there are quite a few sources of error in this experiment. One source of error comes from the tube of the device. The Legos themselves are able to scatter the incoming light from the source and this will affect the spectrum. Diffraction caused by the Legos will alter the light that is incident on the diffraction grating. Absorbance by the Legos might also lower the intensity of the light at certain wavelengths that hits the diffraction grating. We used black Legos to minimize the effects of the absorbance, as the Legos should absorb more in the infrared than the visible spectrum. If one used colored Legos, this would have to be controlled for, as they would absorb some wavelengths in visible spectrum, which is our region of interest. Another source of error comes from the orientation of the spectrum. The spectrum was oriented so that the rainbow pattern was as horizontal as possible. Deviations from a spectrum aligned on axis would cause the program used to generate the spectrum from the image to possibly over or undercount the intensity of wavelengths. As mentioned before, the spectral response of the CCD camera used to capture the image is also a source of error. The camera of the iPhone 5S is a custom Sony Exmor RS device, which is a Complementary Metal-Oxide-Semiconductor (CMOS) type device. These devices seem to generally respond more to higher wavelengths, reaching a maximum response somewhere around 700 - 1000 nm. This means that our spectra will be skewed, with higher wavelengths responding more. This should not cause too much of an issue as the solar spectrum reaches a maximum intensity at lower wavelengths in the range of 500 nm. It will however effect the fit some, showing a broader peak than it actually is. The best way to correct for this would be to utilize a detector which shows nearly constant response in the visible region. As the device is rather simple, the spectral resolution leaves a lot to be desired. This limitation became very apparent in the calibration procedure. Some of the peaks were ill defined which made it accurately to assess which peaks need to be selected for the calibration procedure. A sharper spectrum would make the calibration much more accurate and therefore help to nail down the wavelengths in the solar spectra. As we are interested in finding the wavelength of maximum intensity this is most likely the largest source of error. The uncertainty on our x-axis was determined to be about 2 nm. This value was obtained from the width of the widest peak used in the calibration procedure. It may seem as if the FWHM value would be more appropriate and not the base width, but as there is error inherent in the orientation of the spectra we found it better to proceed with caution and implement the larger value into our uncertainty.

## VII. Conclusion

In conclusion, we have carefully implemented the principles behind blackbody radiation and Planck's distribution to cleverly identify a means of estimating the surface temperature of many emitting objects – but of particular interest, our own Sun's photosphere that is over 93 million miles away. By adhering to a very cost-effective and minimal budget, we have used everyday items, such as an iPhone, Legos, and tape and specialized items, such as a diffraction grating, and a webpage application, *Spectral Workbench*, develop a iPhone spectrophotometer that can be precisely calibrated to deduce wavelengths and intensities of visible light emission from the Sun. Using this observational data, we can extrapolate the blackbody radiation curve in its entirety and ultimately determine the surface temperature of the sun by finding the wavelength that maximizes intensity. Associated with all of these measurements are a variety of sources of errors ranging from the simplicity of the spectrophotometer design (and iPhone detector), the atmospheric conditions (i.e. $O_2$ and $H_2O$ absorbance in atmosphere), errors associated with the *Spectral Workbench* application, errors in calibration techniques, and finally, error in fitting routines. All of these errors have been carefully tracked, reported, and included in the final reporting of the surface temperature of the sun and the uncertainty in measurement which we ultimately find to be $T = 6000 \pm 300$ K which is a mere 3.8% in difference from the known value. We have also, unexpectedly, identified atmospheric molecule absorptions in our spectra around ˜640 nm which give further merit to our spectrophotometer's abilities to accurately measure blackbody radiation. Future endeavors in this work involve applying ***Helios*** to a variety of other systems that can be modeled by a blackbody radiation curve to see if our calibration, observational, and analytical techniques again yield excellent fits.

## VIII. Costs

-iPhone 5S Case: $4.88
-Tape: $4.86
-Glue: $3.97

**Sum (w/ tax): $14.67**

## IX. References


-Darmon, Arnaud. (2009). *Spectral Response of Silicon Image Sensors.* Aphesa. www.aphesa.com.

-McQuarrie, Donald A.; Simon, John D. Physical Chemistry: A Molecular Approach. University Science Books (1997).

-Phillips, K. J. H. (1995). *Guide to the Sun.* Cambridge University Press. pp. 4753. ISBN 978-0-521-39788-9.

-Zhao, Y. PHYS 3330: Optics (2012). *Chapter 2: Blackbody Radiation.* Department of Physics and Astronomy, University of Georgia.