An Experiment to Determine Solar Limb Darkening using RSpec Spectroscopy Software

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Abstract

Limb darkening refers to the lessening of intensity from the center of the Sun to the edge or "limb" of the Sun. The measurement of this effect can be employed as a unique experiment in undergraduate astronomy or physics laboratories. Several techniques are presently available to determine the numerical intensity values across the Sun's surface, however, RSpec, a real time spectroscopy analysis software program, can be utilized in an unusual way to easily acquire the intensity values needed to verify the limb darkening coefficients with theoretical values.

1. Introduction

The Sun is not equally bright all over, it darkens as you look towards the limb. Photospheric light travels through an absorptive medium. One can see only so far into the photosphere. This effect is refered to as the optical depth, L, Figure 1. At the limb, the line of sight sees the top of the photosphere. At the center, the line of sight sees deeper into the sun to an optical depth of about ⅔ into the photosphere.

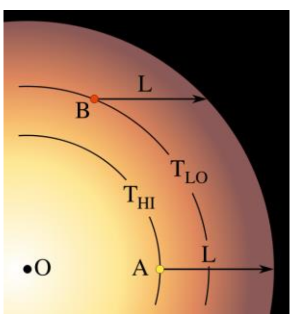

Figure 1 – Optical Depth *(Wikipedia)*

Limb darkening can be explained as the result of two major effects:

a) The density of the star diminishes as the distance from the center increases.
b) The temperature of the star diminishes as the distance from the center increases. The Sun's effective temperature, $T_{eff,}$ is a measure of the Sun's radiation coming from the deepest part of the photosphere (T = 6400K) visible at the Sun's center to the "upper photosphere" or temperature minimum region (T = 4400K) visible at the limb. Since the luinocity is proportional to T_{eff}^4 we therefore see a decrease of solar intensity with an increasing angle toward the limb.

Since the source spectrum is approximately a blackbody radiator in both instances, the radiation coming from the hot material near the center of the disk will be more intense and is more pronounced at the blue end of the spectrum and less pronounced at the red end. For example, at a wavelength of 600 nm, the limb darkening coefficient u = 0.56, whereas at 320 nm u = 0.95 *(Tatum).*

To measure the effect, limb darkening geometry must be determined, Figure 2. The star is centered at O with a radius R . The observer is at point P, a large distance, r, from the center of the star. We look at a point S on the surface of the star. From the point of view of the observer, S, is an angle θ from a line through the center of the star, and is at an angle Ω.to the edge or limb of the star.

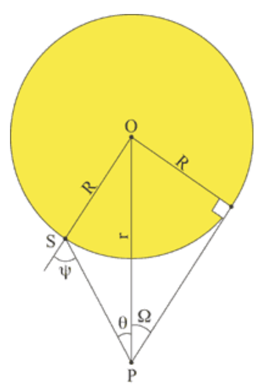

Figure 2 – Limb Darkening Geometry *(Wikipedia)*

Various analytical laws have been suggested for approximating stellar limb darkening, most of them in the form of linear combinations of simple functions of μ (cos Ω). The most basic limb-darkening law, generally referred to as "linear limb darkening," and is given by

$$I_L(\mu)=Io[1-\mu(1-\cos\mu)]$$

μ = cos Ω, angle between the normal to the stellar surface and the line of sight to the observer.

Io = the intensity of light in the center of the stellar disk (Ω=0)

μ = is the wavelength dependent limb darkening coefficient (<1)

The linear limb-darkening coefficient, u, determines the shape of the limb-darkening profile Other laws have been introduced to yield a more accurate analytical description by adding a third term to the equation, such as a quadratic, square root, or logarithmic term (*Claret*). We will utilize the basic linear equation for our experiment.

A graph of six theoretical μ values are calculated and plotted from the lowest curve upward, μ = 1.0, 0.8, 0.6, 0.4, 0.2 and 0.0, Figure 3.

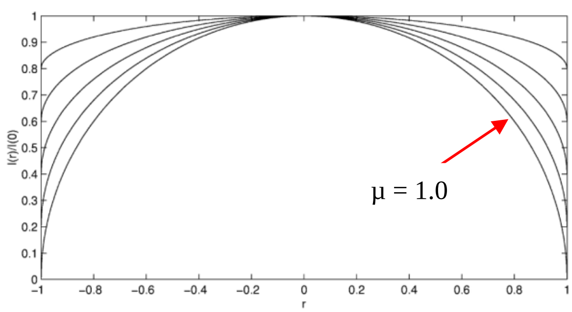

Figure 3 – Limb Darkening Theoretical Plot (*Tatum*)

Utilizing images of the sun at various wavelengths we should be able to reasonably duplicate the theoretical curves for the related μ values.

A Calcium-K narrow band filter allows the camera to see only blue light with a wavelength of 393.4 nm. A white light solar filter should produce a generalized curve with contributions from the blackbody continuum, Figure 4. An infrared filter allows the camera to see only red light with a wavelength of 1.5 microns (1500 nm).

Expensive filters and related telescopic equipment are not necessary in this application as acquiring solar images from the internet in Calcium-K, white light and infrared should yield solar profiles which can be used very effectively in obtaining limb darkening curves which can then be compared to the theoretical values *(Neckel).*

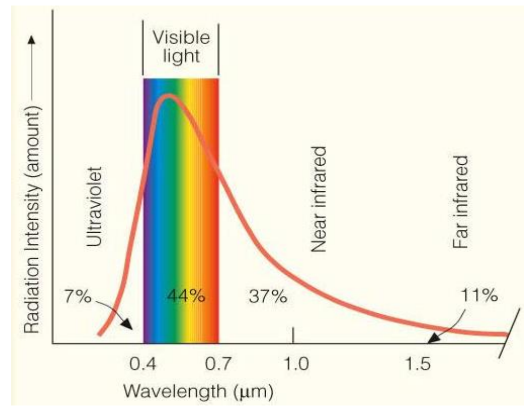

Figure 4 – Blackbody Solar Emission *(Thomson)*

2. Data

RSpec *(RSpec)*, a powerful spectroscopic analysis software program can be utilized in an atypical way. Typically RSpec converts a spectrum into a wavelength profile. If a standard image is imported instead of a spectrum, an intensity profile can be obtained across that image. Images of the sun at different wavelengths were collected from several internet sources (Figures 5, 6 & 7). Images were chosen where the sun would have the same angular size in each image to simplify profile comparison.

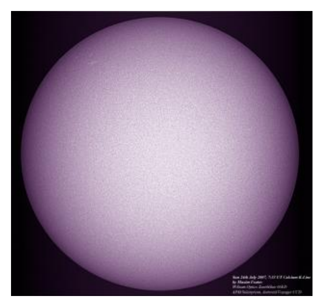

Figure 5 - The Sun in Calcium-K Light *(Usatov)*

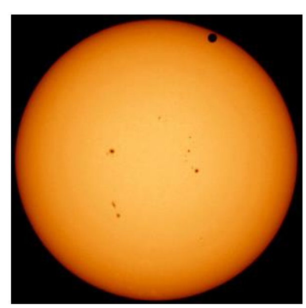

Figure 6 - The Sun in Visible Light *(Wikipedia)*

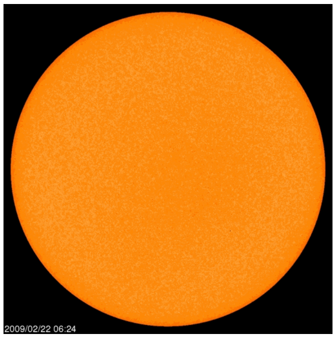

Figure 7 - The Sun in Infrared *(Penn & Livingston)*

Solar images are imported into RSpec, Figure 8, and intensity profiles of each obtained, Figure 9. Data files of the profiles are then exported from RSpec and imported into an Excel spreadsheet for calculations and graphing.

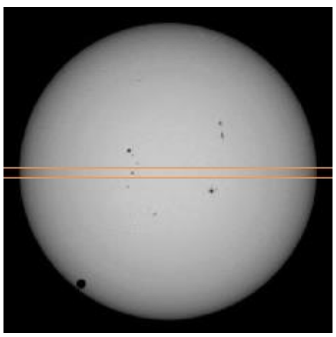

Figure 8 – RSpec Imported Image with Sampling Line.

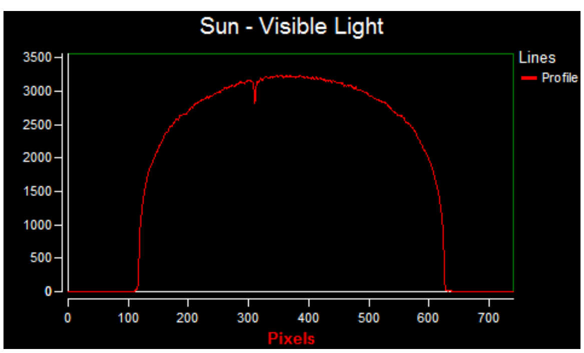

Figure 9 – RSpec Profile (Note the sunspot that appears within the profile line)

3. Results

The three specific profiles in the Excel spreadsheet are then normalized in the intensity vertical axis and are centered on $\Omega = 0$ (center of the sun) on the horizontal axis. A graph of the three profiles is then generated by Excel, Figure 10.

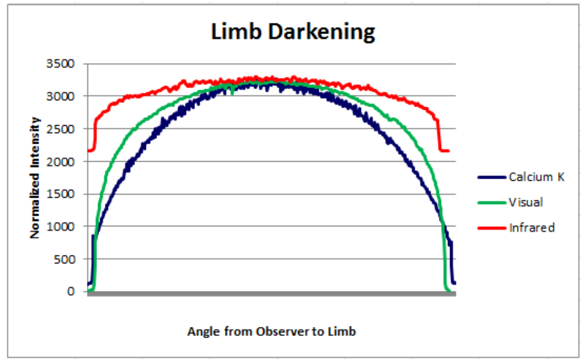

Figure 10 – Limb Darkening for Calcium-K, White Light and Infrared Wavelengths *(Excel)*

4. Conclusions

Acceptable intensity profiles are displayed for the images of the sun that were selected from the internet. After normalization the combined profiles yield a good approximation to the theoretical curves for various limb darkening coefficients, μ.

The limb darkening effect is obvious in each graph and the wavelength dependence can be plainly seen.

Many images on the internet show profile asymmetries and some brighten at the limb. This may be from artifacts of the filters or optical systems. Extremely narrow band filters may also introduce asymmetries due to the Doppler Effect. Several images at each wavelength therefore need to be previewed to acquire a single consistent symmetrical image for use at each wavelength in the experiment. Hydrogen alpha filter images should not be used since this filter effectively looks above the photosphere at portions of the chromosphere. Limb brightening also occurs in these images because prominences, sunspots, and very bright major flares are present at the limb.

The exercise does yield good results and allows the students to familiarize themselves with the limb darkening effect without the use of expensive specialized telescopes or filters.

5. Acknowledgements

I would like to thank Michael Burin, CSUSM Physics Department, for his student limb darkening experiment and Tom Field, RSpec Real Time Software, for his program which had an unplanned additional capability.

6. References

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