Measuring the Solar Luminosity in the Undergraduate Laboratory Using the Thermal Conductivity of an Aluminum Plate

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The solar luminosity is an excellent candidate quantity for undergraduate laboratory measurement that holds historic significance in astrophysics. We aimed to measure the luminosity of the Sun with the low-cost method of thermal conductivity and proposed an additional method with a photodiode. Through the thermal plate heating method, we found a solar luminosity of (3.5+/- 0.5)×10^{26} W, which is within 7.4% of the accepted value. Future considerations include the completion of the complementary photodiode method.

Plate-Heating Method

Description

Solar luminosity is an important constant in unraveling the Sun's production of energy. We measured the solar irradiance at the surface of the Earth and accounted for the atmospheric light extinction to get an absolute estimation of solar irradiation and thus the solar luminosity. We present a simple low-cost apparatus using Aluminium plates and temperature probes to measure the the rate of change in temperature due to solar irradiation.

Eq. 1
$$\left.\frac{dT(t)}{dt}\right|_{t=t_0} = \frac{\varepsilon}{\rho_p c}\frac{I_{gnd}}{t_p}$$

The slope of the curve T(t) when the temperature of the plate is equal to ambient temperature T_0 is proportional to the solar irradiance at the ground I_{gnd}. Accounting for atmospheric light extinction, we determined the solar irradiance, I_0. This value is then related to solar luminosity L using:

Eq. 2
$$L = 4\pi d^2_{Sun-Earth} I_0$$

Methods

1. Spray painted aluminum plate of size 30.7 cm by 30.7 cm (+/- 0.1 cm on each side) and thickness 2.20 +/- 0.05 mm matte black
2. Characterized reflectance of plate using spectrometer
   - Collected the spectrum of light from an incandescent bulb reflected by the plate and compared this to the bulb's unimpeded spectrum
   - Reflectivity of 1.56% in the wavelength range (400-900 nm)
3. Attached four LoggerPro temperature probes as seen in Fig. (ref)
4. Collected data on clear, sunny, and windless days
5. Cooled plates with dry ice
6. Adjusted box to perpendicularly align with incident sunlight
7. Recorded ambient temperature with mercury thermometer
8. Recorded time and geographical location to find the zenith angle of the Sun
9. Calculated K_{eff} from multiple measurements
10. Calculated solar luminosity with Eq. 2

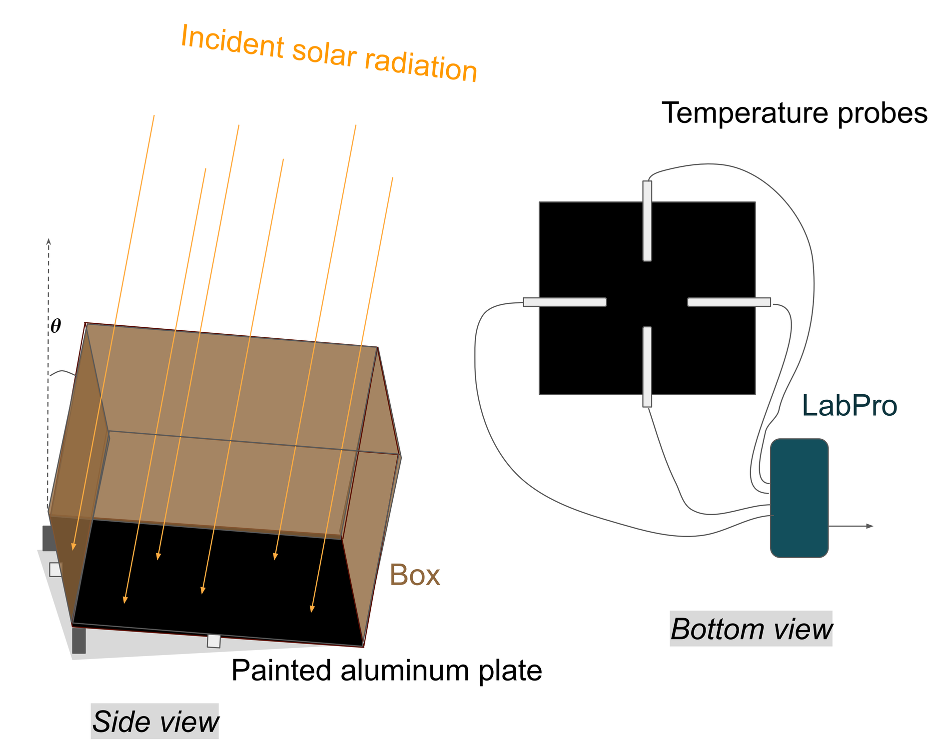
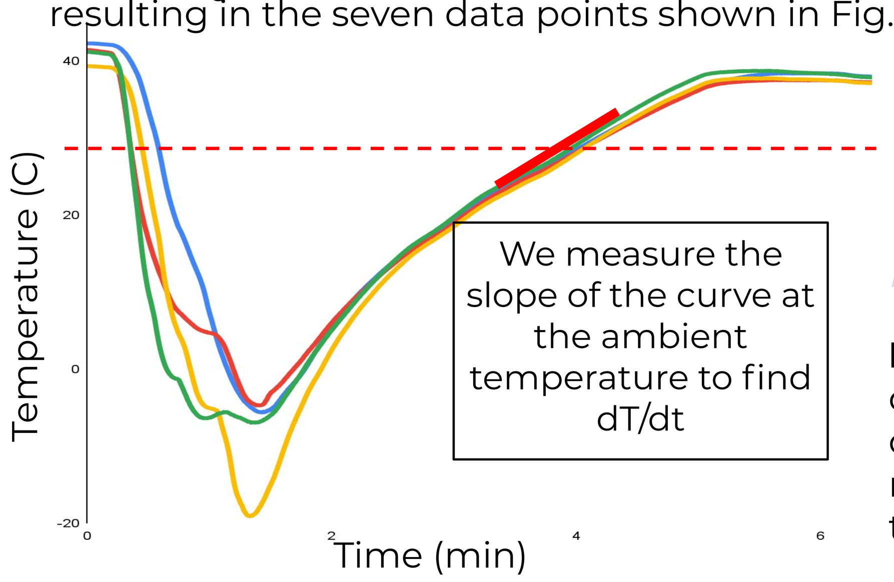


Fig 1: The side view of the apparatus shows the black surface of the aluminum plate exposed to the solar radiation. We adjusted the box to the correct angle **θ** so incident light hit perpendicular to the plate. The plate is contained within a cardboard box.

The bottom view shows the placement of the LoggerPro temperature probes. Four are attached on each side of the plate. The data collected from these probes is sent to the LabPro for analysis.

Results

Fig. 2: Plot of temperature over time measured by the four sensors on the bottom of the plate for one of the sample runs. We used LabPro to determine *dT/dt* at ambient temperature. This gives us I_{gnd} via Eq. 1. This process was repeated, resulting in the seven data points shown in Fig. 4.



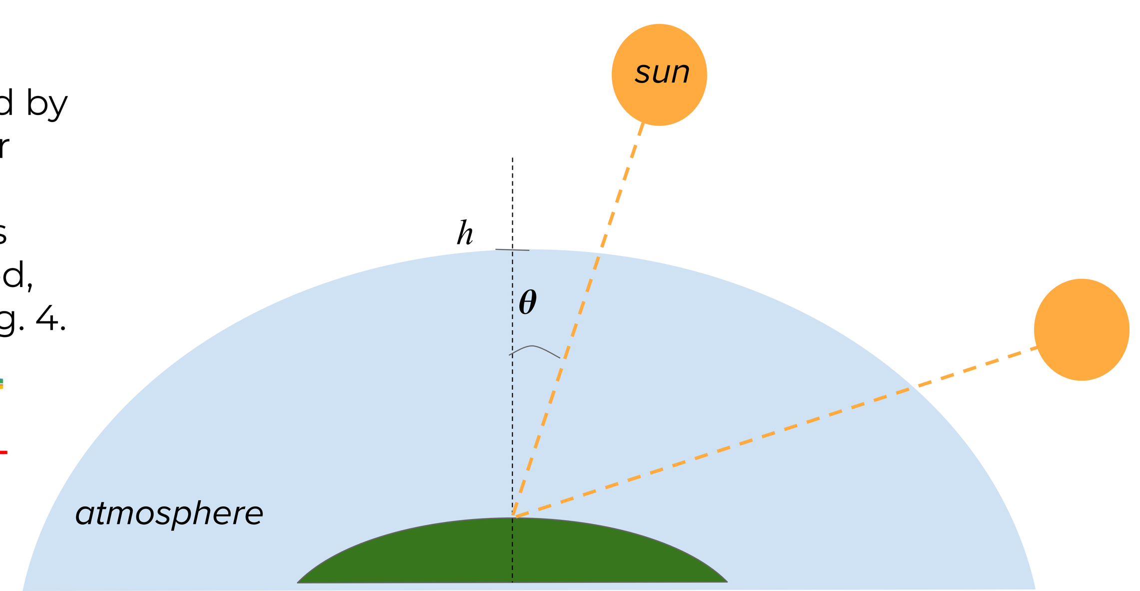


Fig. 3: The amount of atmospheric extinction varies with cos(*θ*), where *θ* is the zenith angle of the sun (see Eq. 3). We can experimentally determine the amount of extinction by making measurements at different zenith angles (different times of day).

We measured the atmospheric extinction coefficient and the solar constant by measuring I_{gnd} as a function of the solar zenith angle and plotting the following relationship:

Eq. 3
$$\ln(I_{gnd}) = -K_{eff}/\cos(\boldsymbol{\theta}) + \ln(I_0)$$

I_{gnd} = solar irradiance at ground level

I_0 = solar irradiance

K_{eff} = effective atmospheric extinction coefficient

$\boldsymbol{\theta}$ = solar zenith angle

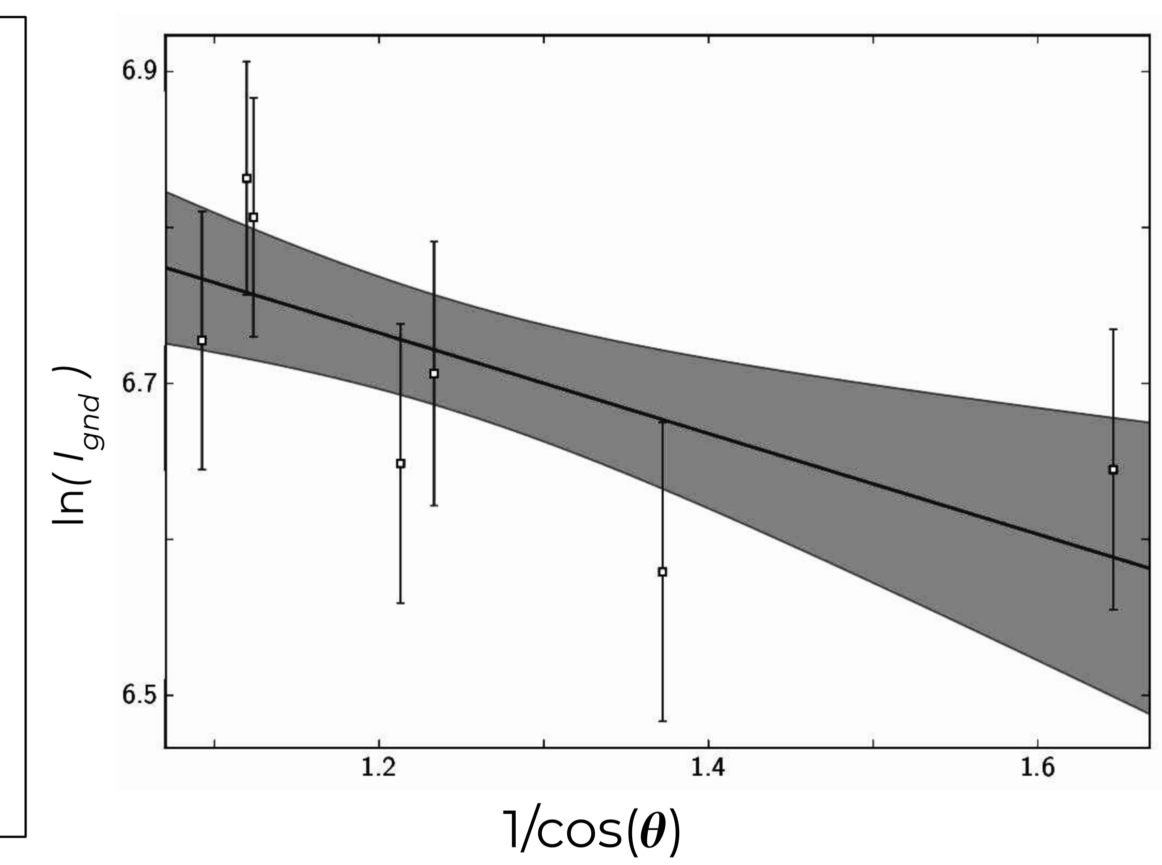


Fig. 4: Plot of I_{gnd} versus 1/ cos(*θ*). According to the equation to the left of the plot, we experimentally determined the amount of extinction and the solar constant I_0 by varying the zenith angle. From this plot, we obtained values of K_{eff}=0.3 +/- 0.1 and I_0=1300+/- 200 W m^{-2}.

We obtained a measurement of the solar constant of I_0=1300+/- 200 W m^{-2}, which gives a value of the solar luminosity of L_0=(3.6+/- 0.5)×10^{26} W via Eq. 2.

Photodiode Method: Future Consideration

An inexpensive photodiode amplifier system can be constructed to measure the solar irradiance where the luminous power output measured by the photodiode is proportional to the luminous power output of the Sun, given by:

Eq. 4
$$P_{pd} = P_{\odot} FAB$$

F is the geometric dilution, A is the fraction of sunlight transmitted through the atmosphere and B is the actual sunlight detected despite spectral bandmass mismatches.

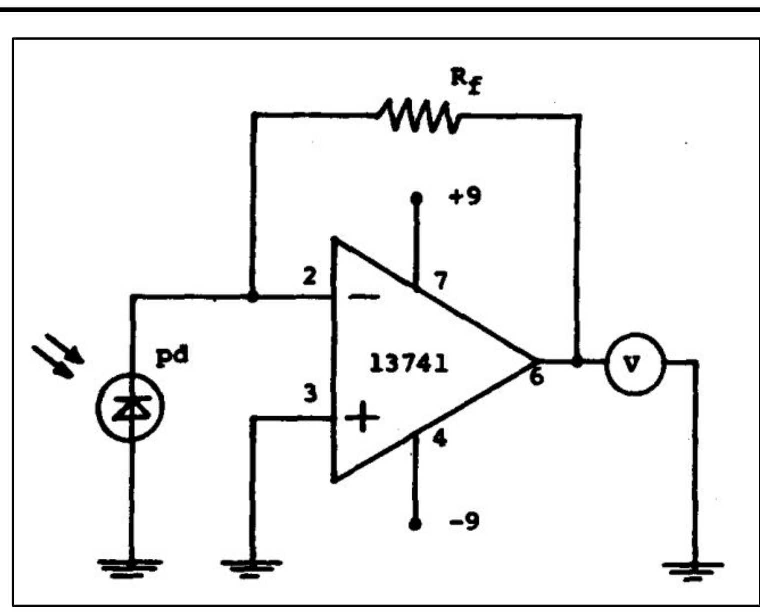


Fig. 5: The op-amp circuit to measure solar photodiode current [2].

The power measured by the photodiode is proportional to the output voltage across a feedback resistor, R_f, and the spectral responsivity of the photodiode, *S*.

Eq. 5
$$P_{pd} = (V_{out}/R_f)\,S$$

Possible Challenge: We found that a largely insensitive photodiode amplifier system is needed as the solar power output is extremely high and can lead to oversaturation.

Conclusion

Using a painted, heat-conducting aluminum plate and four temperature sensors, we measured the luminosity of the sun to be (3.5+/- 0.5)×10^{26} W, which is within 7.4% of the accepted value. This method improved on that of Ref. [1] by simplifying the apparatus using inexpensive tools for the undergraduate laboratory, while still maintaining a comparable level of accuracy to their result. Future improvements include refining the measurement of the plate's reflectivity and reducing the effects of wind and condensation during the cooling process. We investigate a second technique, the photodiode method, which may provide a secondary measurement for comparison that is also highly affordable and at the undergraduate level [2]. This work provided an inexpensive measurement of an important and historically significant parameter in astrophysics, and can be used as a framework for a low-cost, undergraduate-level daytime astronomy exercise.

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References

[1] S. Gil, M. Mayochi, L. J. Pellizza, *Am J Phys* 74, 728–733, ISSN: 0002-9505 (2006).
[2] D. L. DuPuy, eng, *Am J Phys* 57, 826–828, ISSN: 0002-9505 (1989).