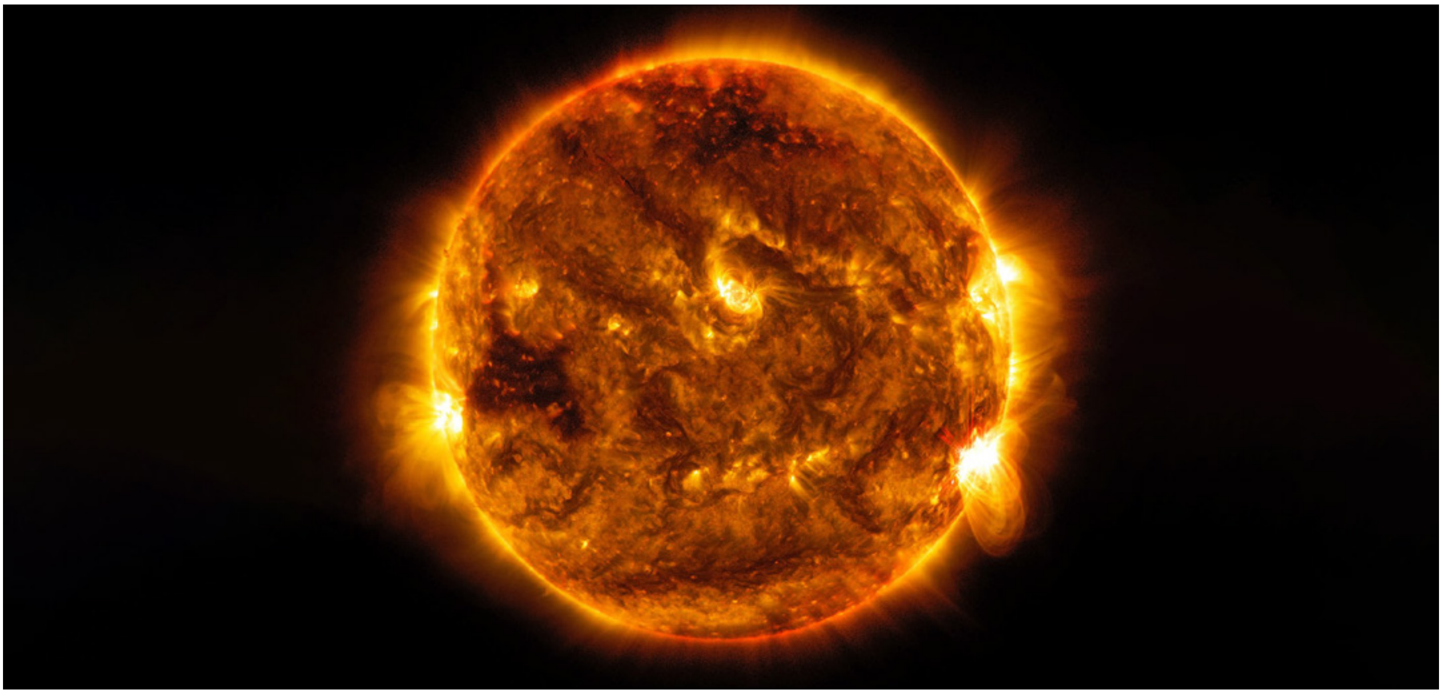
Science in School
The European journal for science teachers

ISSUE 72 – April 2025 **Topics** Astronomy/space | Earth science | Engineering | Mathematics | Physics



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Estimate the Sun's temperature without leaving the school

Ioannis Kardaras

Starstruck: with just water, sunlight, and simple equipment, students can use their physics knowledge to calculate the temperature of the Sun.

The Sun, our nearest star, plays a vital role in sustaining life on Earth. It is a source of light and heat, and its crucial role has been acknowledged since antiquity, as evidenced by its veneration in numerous ancient cultures. Over the years, as scientific understanding deepened and technology advanced, scientists have managed to study the Sun and calculate key characteristics like its temperature. We might think someone needs expensive equipment and profound knowledge of astrophysics to calculate the temperature of the Sun, but this is far from reality. Students may be surprised to learn that they can calculate the Sun's temperature without the need for sophisticated instrumentation.

The main question

How can we calculate the Sun's temperature based on the observed temperature change of a water mass over a defined time interval at noon on a warm, sunny day?

With the following activities, we encourage students to utilize readily available materials and their acquired physics knowledge to determine the temperature of the Sun’s photosphere. The learning scenario incorporates active learning and students are fostered to develop creativity, since they are challenged to tackle a complex problem that requires them to apply physics principles to astrophysical procedures. Teaching physics in the context of stars opens a captivating window into the vastness of the Universe for students and ignites their curiosity to understand the underlying physics of these celestial bodies.

This activity is most suited to students in the upper secondary level, who possess a solid grounding in the principles of heat and radiation, as well as fundamental algebraic and geometric concepts.

Learning objectives

1. Establish the relationship between heat transfer (Q), specific heat capacity (c), mass (m), and temperature change (ΔT) for a given substance.[1–4]
2. Recognize that light intensity decreases inversely proportionally to the square of the distance from the energy source.
3. Understand that all objects emit thermal radiation in the form of electromagnetic waves, governed by the Stefan–Boltzmann law, $P = A\sigma T^4$, where P is the rate of heat transfer (energy radiation), A is the area of the emitting surface, σ is the Stefan–Boltzmann constant (5.76×10^{-8} J/s m^2 K^4), and T is temperature.

Optional introductory activity: Inverse square law for light intensity

If students are not yet familiar with the inverse square law, some simple experiments can be carried out to demonstrate this relationship as an optional introductory activity (see the supporting material).

Activity 1:

Heat transfer and absorption

In this activity, students measure the rise in the temperature of water contained in a glass jar and exposed to the Sun. Then, using this data, they calculate the energy needed for this rise using the relationship that the heat absorbed by an object with mass m and specific heat c changes its temperature according to the equation $Q = mc\Delta T$.

This activity should take around 40 minutes.

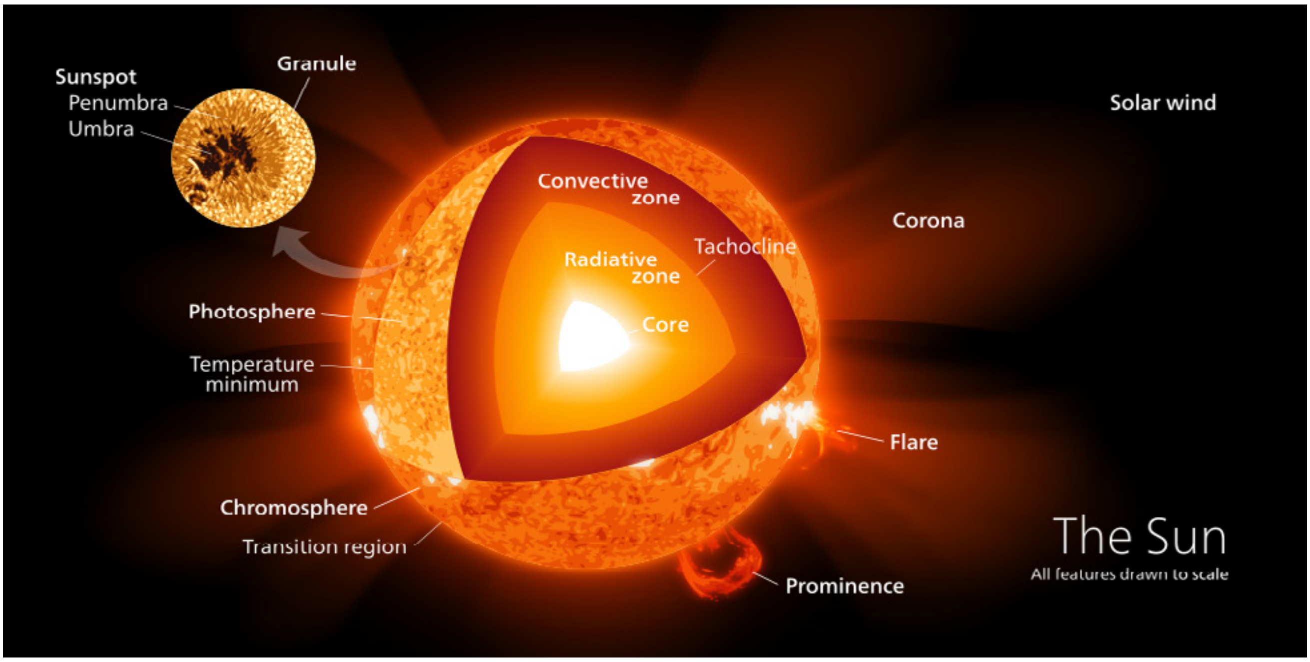
Materials

- Student Worksheet 1
- A glass jar of water with a capacity of 400 ml
- A thermometer

Procedure

Making the measurements

1. Divide students into groups of three. This will allow everyone to participate and collaborate on the experiment.



Sun’s photosphere is the visible surface of the Sun and emits most of the Sun’s light that reaches Earth directly.

Image: Isadoraoflbiza/Wikipedia, CC BY-SA 3.0

2. Each group fills a glass jar with 400 ml of water. Bear in mind that 1 ml of water is approximately equal to 1 g, so there will be about 400 g (0.4 kg) of water.
3. Before placing the jar in direct sunlight, each group carefully inserts the thermometer and records the initial temperature of the water. To prevent evaporation phenomena and for better reliability in the measurements, make sure to close the jar with a lid with a hole for the thermometer. If the jar doesn't have a lid, one can be made with a piece of cardboard.
4. Place the glass jar in direct sunlight. Make sure all groups place their jars in a similar location so that the amount of sunlight received is relatively consistent.
5. Each group records the water's temperature at specific times for a total of 20 minutes. This means students will have temperature readings at 5, 10, and 20 minutes, which they record in a table on worksheet 1.

Analyzing the data

6. For each time interval (5, 10, and 20 minutes), calculate the change in temperature (ΔT).
7. Then using the equation $Q = mc\Delta T$, calculate the amount of heat energy (Q) transferred from the Sun to the water. Remember, the specific heat capacity of water (c) is approximately 4186 J kg–1 °C^{-1}.
8. Students then calculate the rate at which heat energy is transferred using the equation $P = Q/t = (mc\Delta T)/t$. Just like electrical power measures the flow of electricity, thermal power measures the flow of heat.

See the sample data below:

Time (min)	Time (s)	Temperature (°C)
0 starting point	0 starting point	26
5	300	27
10	600	29
20	900	32

The overall change in temperature, $\Delta T = 6°C$

Energy transfer,

$Q = mc\Delta T = 0.4 \text{ kg} \times 4186 \text{ J kg–1 °C–1} \times 6°C = 10\,046.4 \text{ J}$

Power, $P = Q/t = 10\,046.4/1200 = 8.3 \text{ J/s}$

Image courtesy of the author

Results and discussion

By calculating the power (P), we have essentially estimated the amount of solar energy that reaches the water in the jar per second. In other words, we have measured the power of sunlight as it reaches the Earth's surface at a specific location. We can then use this to calculate the Sun's total power output by considering factors like the Earth's distance from the Sun, the Earth's curvature, and the energy absorbed by the atmosphere – this is the task for Activity 2.

It's important to recognize that the experiment has potential sources of error. For instance:

- The glass jar itself absorbs some heat, so some of the Sun's energy goes into heating the glass, not just the water.
- Wind, clouds, and changes in the Sun's angle can all influence the amount of sunlight reaching the jar.
- The jar will lose heat to the surrounding air.
- Reading of the thermometer gives a percentage of uncertainty in the measurements.

Possible improvements:

- Use a thinner-walled container or a container made of a material with a lower specific heat capacity.
- Use a more precise thermometer and read the temperature value at eye level.
- Conduct the experiment on a clear, windless day.

Activity 2: Calculating the Sun’s photosphere temperature

With an understanding of the inverse square law and having established the heat transfer rate in Activity 1, students are ready to proceed to this activity concerning the calculation of the temperature of Sun’s photosphere using the Stefan–Boltzmann law, which posits that the rate of energy absorbed by a surface is directly proportional to both the surface area and the fourth power of its absolute temperature (T) in Kelvin. Stefan experimentally determined this relationship in 1879, while Boltzmann subsequently provided a theoretical derivation.[1]

This activity should take around 40 minutes.

Materials

- Student Worksheet 2
- A cylindrical food or soft drink can, which is painted black and has a hole in the top for the thermometer
- A thermometer
- A clamp stand

Note

As a reminder, the conversion from Celsius to Kelvin temperature involves adding 273.15 to the Celsius value.

Procedure

Initial discussion

1. Prior to commencing the activity, as a class, discuss the relationship outlined in the Stefan–Boltzmann law. This law posits that the rate of energy absorbed by a surface is directly proportional to both the surface area and the fourth power of its absolute temperature (T) in Kelvin. Mathematically expressed as intensity of radiation (I), which is power per unit area with units W/m^2, the Stefan–Boltzmann law equates power (P), or the rate of energy emitted via electromagnetic radiation, to the product of the Stefan–Boltzmann constant (σ) and temperature (T) raised to the fourth power: $I = \sigma T^4$.
2. Students then perform a similar experiment to Activity 2 and use astronomical data (Sun–Earth distance, Sun’s radius) to calculate the Sun’s total radiated power. Remind students that they have learned how to estimate the power of the Sun at the Earth and determine the solar irradiance on Earth (power per unit area). This irradiance, combined with the Sun–Earth distance, yields the Sun’s total power output. Finally, students apply the Stefan–Boltzmann law to calculate the Sun’s temperature and compare it to the accepted value, calculating absolute and relative errors.
3. Write the necessary astronomical data on the board, and the students copy it onto their worksheets. Alternatively, students can research these values.

Image courtesy of the author

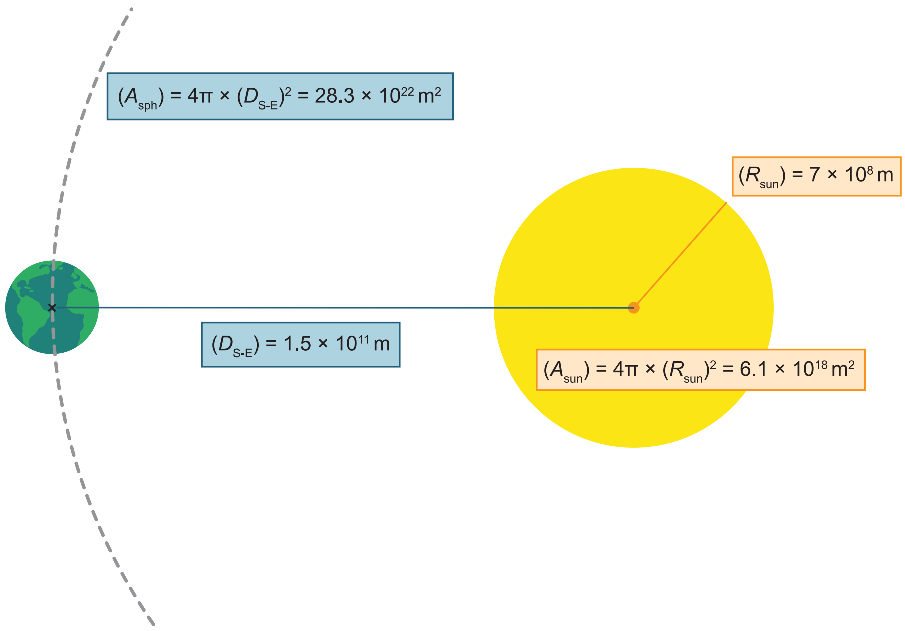


Image courtesy of the author

- Average distance between the Sun and the Earth $(D_{S\text{-}E}) = 1.5 \times 10^{11}$ m.
  Note: the Earth's orbit is elliptical, so the distance varies and latitude and season affect the angle of incidence of sunlight.
- Radius of the Sun $(R_{sun}) = 7 \times 10^8$ m
- Surface area of the Sun $(A_{sun}) = 6.1 \times 10^{18}\ m^2$
- Surface of a sphere with a radius equal to the distance between the Sun and the Earth $(A_{sph}) = 4 \times \pi \times (D_{S\text{-}E})^2 = 28.3 \times 10^{22}\ m^2$

Performing the experiment

4. Hand out the black cylindrical cans to the students and ask them to measure the dimensions of it and calculate the area that is projected directly onto the solar radiation (A_{cp} = height × diameter = $H \times 2r$).

The projected area A_{cp} = height × diameter of the cylindrical can = $H \times 2r$

Image courtesy of the author

5. Students then fill the can with water, measure the amount used, and record the initial temperature of the water.
6. Expose the can filled with water to the Sun. Students place the can in the stand, and then they must tilt the can so that its shadow is rectangular, since, in this way, the amount of solar radiation received by the can is maximum and the rise of temperature is greater.[5] If a sealed lid is not feasible, the experiment can be modified to keep the cans vertical. To compensate for the reduced exposed surface area, the exposure time could be adjusted (e.g., 20% longer exposure time).
7. After 15 minutes, students measure the final temperature with the thermometer and calculate the difference between the initial and final temperature.

Calculating the Sun's temperature

8. Students should first calculate the amount of heat required ($E_{can} = Q = mc\Delta T$) for this temperature change and the rate of heat transfer ($P_{can} = Q/\Delta t$), as in Activity 1.
9. Then students determine the solar irradiance, that is, power radiated from the Sun to the Earth per square meter ($P_{SQME} = P_{can} \times (1/A_{cp})$).
10. The radiation reaching the can and the Earth calculated previously depended on the radiation emitted by the Sun and the distance between the Earth and the Sun. Thus, the total power emitted by the Sun (*PS*) can be calculated by multiplying the solar irradiance (power per unit area) incident on Earth by the surface area of a sphere with a radius equal to the Sun–Earth distance ($P_S = P_{SQME} \times A_{sph}$). Alternatively, for steps 9 and 10,

students calculate the total energy output of the Sun $E_{sun} = E_{can} \times (A_{sph} / A_{cp})$ and subsequently estimate the total power of the Sun by dividing the total energy output of the Sun by the exposure time of the can.

11. Subsequently, students can determine the Sun's temperature using the Stefan–Boltzmann law ($I = PS/A_{Sun}$, $I = \sigma \times T^4$).
12. Finally, students are tasked with determining the absolute and relative errors of their measurement. The absolute error is calculated as the difference between the approximated actual value of 5780 K[4] and the measured value. The relative error is subsequently computed as the ratio of the absolute error to the approximated actual value.
    Example for a measured value of 5258 K:
    $(5780 - 5258)/5780 = 0.09$ or 9% error.

Discussion

For students, further exploration can be undertaken to elucidate the equivalence between the equations $Q/t = \sigma A T^4$ and $I = \sigma T^4$, as well as to investigate the phenomenon of increased radiation emitted by disaggregated coals. Reference [6] may provide additional insights. Students should also be encouraged to identify potential sources of error in the experiment, such as inaccuracies in measurements of water mass, experiment duration, temperature, exposure time, and solar angle.

Conclusion

Through these activities, students learn that they can calculate a fundamental characteristic of our solar system (the temperature of the Sun) using simple equipment and knowledge of physical relationships.

Some further discussion points:
Radiant energy is a form of energy transmitted through space in the form of electromagnetic waves. Can students mention types of radiant energy (electromagnetic waves)? Examples are infrared waves, light waves, and radio waves.[2]

Biographical research into the scientists involved in the derivation of the aforementioned relationships and a historical overview of the process can provide valuable context for students.

A practical application of these concepts can be explored through calculating the potential cost savings for a household equipped with a 200-litre solar water heater that supplies warm water at 50°C for six months, assuming an average initial water temperature of 15°C.

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[3] Serway RA, Jewett JW (2014) Physics for Scientists and Engineers with Modern Physics 9th edition. Brooks/Cole. ISBN: 781133953999

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[6] Urone P, Hinrichs R (2022) *College Physics* 2nd edition. XanEdu Publishing Inc. ISBN: 978-1711470832

Resources

- Read about the correlation between temperature and radiation.
- Explore electromagnetic radiation.
- Download the phyphox app to measure light levels with a smartphone.
- Explore greenhouse gases and radiation.
- Read about a similar experiment.
- Learn all about the Sun.
- Experience cutting-edge science with your students at the Xcool Lab at European XFEL: Aretz S (2024) Xcool Lab at European XFEL: a place to spark students' scientific curiosity. *Science in School* **70**.
- Discover the concept of harmonic motion with sunspots: Ribeiro CI (2016) Sunspots on a rotating Sun. *Science in School* **35**: 37–40.
- Get your students to use their smartphones for some hands-on astronomy: Rath G, Jeanjacquot P, Hayes E (2016) Smart measurements of the heavens. *Science in School* **36**: 37–42.
- Build a solar cooker and learn about the thermoelectric effect with Peltier modules: Mancini P (2023) Cooking with sunlight and producing electricity using Peltier modules. *Science in School* **61**.
- Investigate light spectra using a home-made spectrometer: Ribeiro CI, Ahlgren O (2016) What are stars

made of? *Science in School* **37**: 34–39.

- Measure the circumference of the Earth like Eratosthenes did 2300 years ago: Malamou S, Kitsakis V (2023) The Eratosthenes experiment: calculating the Earth's circumference. *Science in School* **63**.
- Use a light bulb to explore why stars shine in different colours: Ribeiro CI (2015) Starlight inside a light bulb. *Science in School* **31**: 37–42.
- Learn how to detect manipulated night-sky photography: Muñoz Mateos JC CSI Astronomy: learn how to spot fake astrophotography images. *Science in School* **69**.
- Explore some of the science behind our efforts to harness fusion energy: Tischler K, de Vries G (2023) The everyday science of fusion. *Science in School* **63**.
- Learn more about the Sun and its source of power: Westra MT (2006) Fusion in the Universe: the power of the Sun. *Science in School* **3**: 60–62.
- Discover how astronomers study the past of the Milky Way and peer into its future: Forsberg R (2023) Galactic Archaeology: how we study our home galaxy. *Science in School* **64**.

AUTHOR BIOGRAPHY

Ioannis Kardaras is a physics teacher and a High school Director in Trikala, Greece. Holding a PhD in Astrophysics Didactics, he has two additional Master's degrees: one in Physics Didactics and another in Nuclear Physics. Ioannis has been teaching for twenty years in Greece.