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Estimation of the solar constant with simple bolometer

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Abstract

There are only a few experiments in astrophysics that can be done in the high school environment. Some astronomical observations leading to the estimate of determining the values of various astronomical parameters (radius of the Earth, the Earth–Moon distance, and others) can be done, but the astrophysical measurements usually require specialised equipment, which is beyond the capabilities of most schools. This frontline describes three simple methods that can be used to estimate the solar constant, which is an important astrophysical parameter.

1. Introduction

Solar constant describes the average power of solar radiation incident on the surface of one square meter perpendicular to the direction of arrival of the rays at the upper boundary of the atmosphere of the Earth.

From the academic point of view, the concept of the solar constant is very important because knowledge of its value provides a very vivid way to determine the total luminosity of the Sun and stellar luminosity which is one of the important astrophysical quantities. For this purpose, measurements described here can be used.

Designation *constant* is slightly misleading. The elliptical orbit of the Earth around the Sun causes the change of the incident power by approximately 7% between the first of January when the Earth is closest to the Sun, and on August 3, when the distance between the bodies is greatest. Also, the solar constant is referred to as the average annual value of 1367 $W \cdot m^{-2}$. Moreover, this figure is not final, as the total luminosity of the Sun varies within ±0.25% during a solar cycle.

Due to the still raging business with solar power, it is useful to point out to students that the surface power density available at the surface of the Earth is less than this ideal value. The Earth's atmosphere partially reflects radiation (up to 10%), partially absorbs (especially water vapour, oxygen molecules and ozone), and partially dissipates radiation (Rayleigh scattering deflects the energy of purple and blue photons from the original direction; only less energetic photons retain on original the path).

In addition, there is also the Mie scattering from dust particles which are larger than the wavelength, as well as the absorption and subsequent emission (associated with the partial transmission of radiation energy of dust particles, and increase of their temperature). It is also worth mentioning the role of clouds in the shaping of global climate, partly because the clouds disperse the incoming radiation; but also very much reflect the radiation and thus help cool the Earth's surface. Finally, it is good to emphasise to students that it is necessary to take into account the angle of surface with respect to the direction of incoming beams.

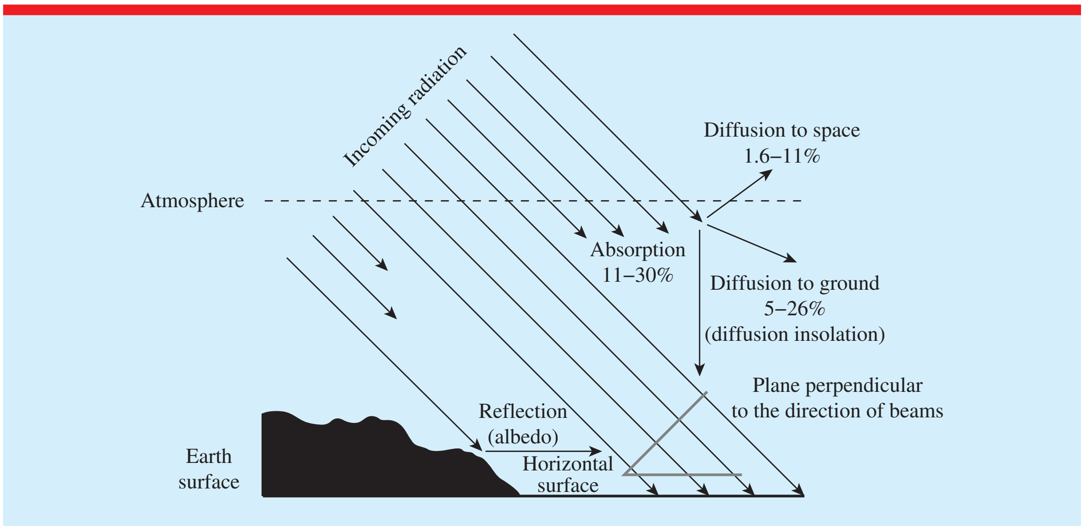

Figure 1. Conversion of solar energy in the atmosphere according to [1].

All of the above energy losses lead to an estimate that the energy available at the Earth's surface by the immediate situation is only 83 to 33% of the energy at the bound limit of the atmosphere. The overall proportions through the atmosphere are in figure 1.

2. Methods

In order to estimate the solar constant, it is possible to use a simple bolometer comprising of an aluminium plate with one surface covered with a thin layer of carbon black which is exposed to sunlight and its temperature is measured over time. If we assume that all the incident energy increase the temperature of a bolometer, then this equation can be applied:

$$\Delta E = mc\Delta T, \tag{1}$$

where m is mass of the bolometer and c is the specific heat capacity of the material used and the temperature change is ΔT. Since the solar constant has dimension of $\mathrm{W \cdot m^{-2}}$, we divide equation (1) by the area of the bolometer and the measured time Δt:

$$I_{\mathrm{SC}} = \frac{\Delta E}{S\Delta t} = \frac{mc\Delta T}{S\Delta t}, \tag{2}$$

Here I_{SC} is solar constant and S is area of the bolometer perpendicular to incident radiation.

In order to avoid the need to separately determine the heat capacity of the bolometer and the thermometer, the temperature is measured by a non-contact infra-red thermometer. The accuracy of measurement is slightly worse, but for school use, it is still sufficient. The heat capacity of the bolometer is determined by measuring the weight and multiplying by the specific heat capacity.

To implement the experiment, an aluminum plate with a surface area of 29.3×28.5 mm, coated with carbon black (for school use, it will be preferable to cover the surface with matte black car paint spray) was used. The weight of the plate was determined to be (15.0 ± 0.1) g by measurement.

The bolometer was set perpendicular to the direction of arrival of the solar rays, and every 15 s the temperature was measured by the infra-red thermometer (see figure 2). Measurements took place shortly after local noon, when the path of rays in the atmosphere is the shortest, and at the time when the sky was clear. The results are in the graph in figure 3.

Of course, the data show (within the range of error of the infrared thermometer) an exponential dependence according the Newton's law of heating [2], converging to the value of 34.6 °C.

Linear dependence was fitted to the measured data points up to the point of 34.6 °C. The error won't be large if we substitute exponential dependence in this interval with linear function. Directive of the linear curve (calculated as 0.0312) defines the quantity $\frac{\Delta T}{\Delta t}$ in equation (2).

Figure 2. Simple bolometer with infra-red thermometer.

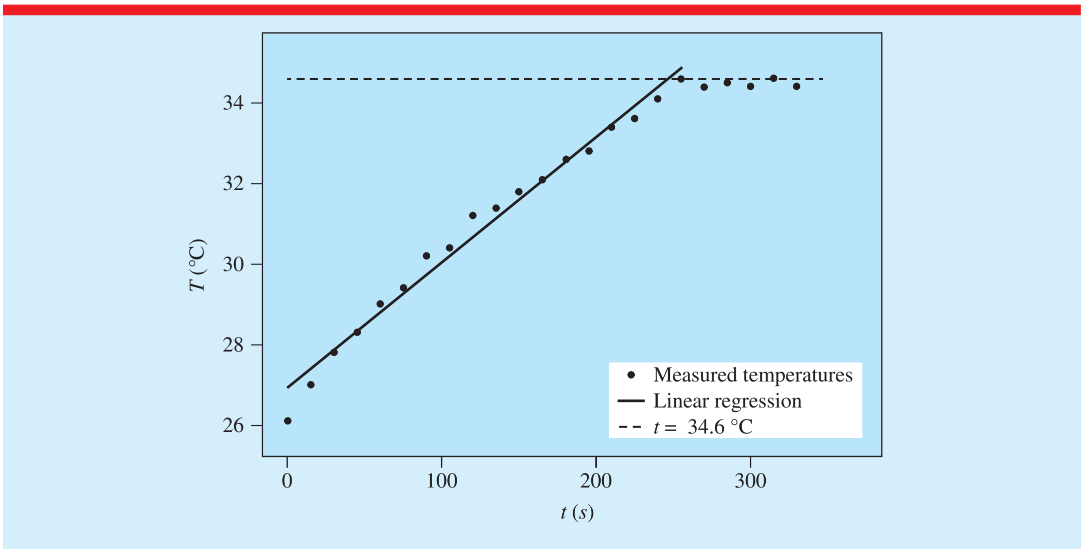

Figure 3. Bolometer temperature versus time.

The calculated value of the solar constant at Earth's surface is then 502 $\mathrm{W \cdot m^{-2}}$.

For the day of observation, the value of solar constant was calculated as 1330 $\mathrm{W \cdot m^{-2}}$. Comparing that with the measured value it is evident that the measurement is not very accurate. In addition to the above physical energy loss during radiation through the atmosphere is the measurement itself burdened with a number of variations which aim to lower results. Radiation of the bolometer and its contact with air cools the surface, surface partially reflects light, and the reflective spectrum of the plate can cause lower temperature measured by the IR thermometer, etc.

The solar constant at Earth's surface can be determined from the data by using another approach: when the temperature reached the value of 34.6 °C, measurement was terminated because the increase in temperature stopped. We can say that at this temperature, the energy supplied by solar radiation equals to the thermal energy radiated by the bolometer by heat loss. If we consider

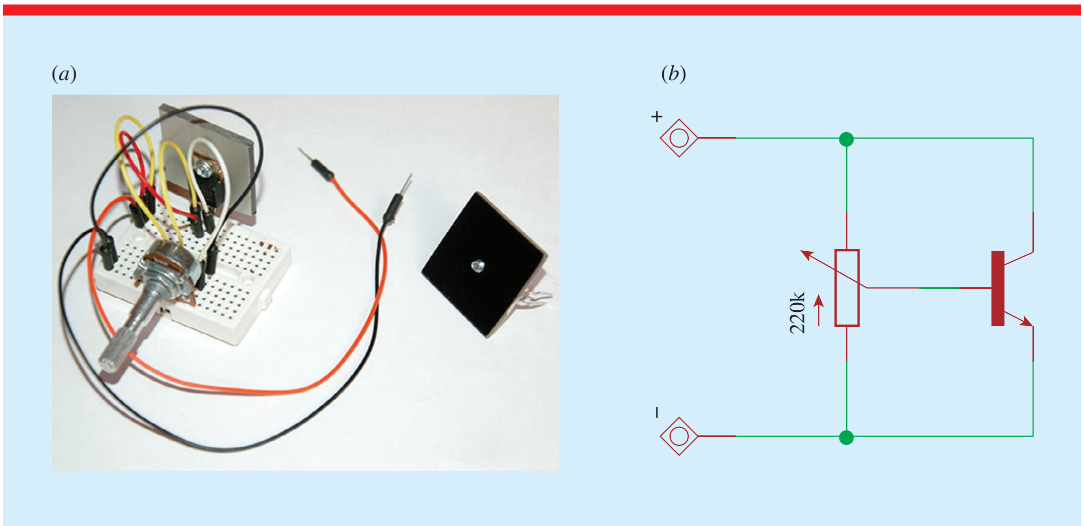

Figure 4. Heating circuit for bolometer. (a) Realisation of the heating circuit for bolometer, (b) schematics of the heating circuit.

the bolometer for an ideal black body, we can apply the Stefan–Boltzmann law to both energies per square meter:

$$I_{SC} = \sigma T^4,$$

where $\sigma = 5.67 \cdot 10^{-8}\,\mathrm{W \cdot m^{-2} \cdot K^{-4}}$ is Stefan–Boltzmann constant and T is the thermodynamic temperature of the bolometer in thermal equilibrium with its surroundings. Substituting the measured values in the thermodynamic scale, we get the radiation flux value of 508 $\mathrm{W \cdot m^{-2}}$, which is a nice agreement with the previous method.

Another option is to use two same plates; one set perpendicular to the rays from the Sun, and the other in the shade. Both plates have a transistor attached, in order to achieve the same heat capacity, whereby the plate in the shadow is heated by the transistor to the same temperature as the plate which is illuminated by the Sun. In this case we can say that the supplied electric power is equal to the power by solar flux (both these energy input to these two systems are maintaining the same temperatures of bolometers). The advantage of this method is that it completely eliminates the necessity of determining the heat capacity of the plates since they are of the same material and have the same dimensions.

To achieve good heat transfer, transistors in TO220 case are especially suitable for heating the plate (see figure 4(a)). By applying a voltage to the base of the transistor (positive for NPN or negative for PNP) the transistor opens and current starts to flow and to heat the transistor with Joule heating). With suitable choice of the supply voltage the temperature can be regulated (dependence of current on the supply voltage can be changed by opening the transistor with the voltage at the base). A simple circuit diagram for the heating transistor is shown in figure 4(b).

During the experiment, the voltage measured across the transistor was $U = 6.1\,\mathrm{V}$ and the current was $I = 78$ mA. This power is for the surface area of $S = 9.15\,\mathrm{cm}^2$. Hence, for the value of the solar constant at Earth's surface, we obtain;

$$I_{SC} = \frac{UI}{S} = \frac{6.1\ \mathrm{V} \cdot 78 \cdot 10^{-3}\ \mathrm{A}}{9.15 \cdot 10^{-4}\ \mathrm{m}^2} = 520\frac{\mathrm{W}}{\mathrm{m}^2},$$

which is quite a nice agreement with the results obtained by the two previous methods.

3. Conclusion

Even though the measurement is not very accurate (is much less accurate than the normal school laboratory measurements), the authors consider this experiment as beneficial because it connects topics that students are already familiar with and also allows to apply the Stefan–Boltzmann law practically. Understanding the concept of the solar constant makes it easy to calculate the total luminosity of the Sun and comprehension of the stellar luminosity.

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