Laboratory Manual

ASTR 24100 Physics of Stars

The University of Chicago

Winter 2019

Labs

1 Spectrum of black body radiation **1**

A Lab Report Format **5**

LAB 1

Spectrum of black body radiation

1.1 Introduction

In this lab you will study the continuous emission of bodies heated to a particular temperature. Such emission can be compared to that of an idealized "blackbody," a term introduced by physicist Gustav Kirchhoff in 1860. A blackbody perfectly absorbs all incident radiation, and thus would appear perfectly black. At the same time, it emits continuous radiation with a spectrum that peaks at a wavelength inversely proportional to the body's temperature.

Although the term may sound mysterious, you see sources of such radiation every day all around you. Incandescent light bulbs that are still commonly used for lighting emit a spectrum very close to that of an ideal blackbody, as you will see in this lab. The Sun light that we enjoy every day also has a spectrum that can be approximated by the blackbody spectrum. Likewise, stars that you see in the night sky emit light with spectra that can be approximated by blackbody spectra. You will check this in this lab for spectra of a few representative stars. This lab also illustrates a very important concept. Physical sciences in general, and astronomy in particular, achieved significant progress because physical laws discovered here and now in the lab turn out to be universally applicable. Thus, for example, you can study Balmer lines of hydrogen from a discharge tube in the lab and then find similar lines in spectra of stars or galaxies. It is this universality that makes science tick. It would be very difficult for us to make sense of astronomical objects, if they worked according to their own celestial laws, not accessible to study in our terrestrial labs. (Yet, this was the accepted view until the scientific revolution of 16th–17th centuries).

In this lab you will employ this powerful concept by first learning how to measure the temperature of a tungsten filament in an incandescent bulb: you will measure the bulb blackbody-like light spectrum with the Red Tide spectrometer, and then apply the same technique to calculate the surface temperature of stars from their spectra.

1.2 Black body spectrum and the Planck formula

The blackbody spectrum has a shape characterized by a broad peak. The peak wavelength position is inversely proportional to the temperature of a blackbody emitting the radiation. This is known as Wein's Law:

$$\lambda_{\max} = 2.9 \times 10^6 \, \mathrm{nm/T} \tag{1.1}$$

Lab tasks.

1.2.1. **We are all blackbody emitters! Estimate the peak emission wavelength for a normal body temperature of 310 K. Which part of the electromagnetic spectrum does this correspond to?**

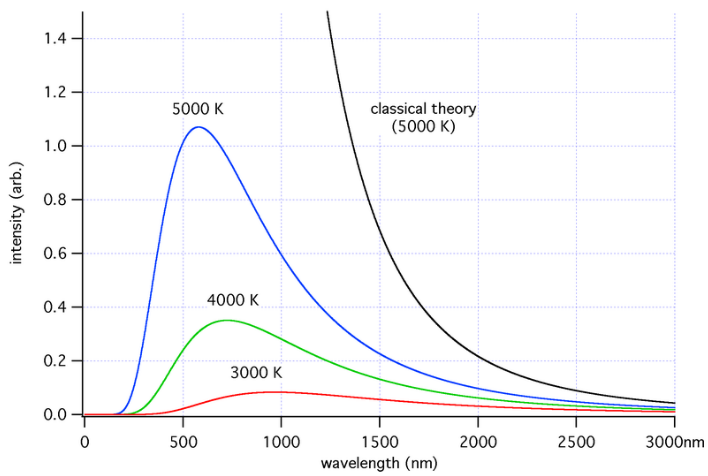

Figure 1.1: The spectrum of radiation emitted by a perfect blackbody at temperatures of 3000K, 4000K, and 5000K according to the Planck formula is shown by red, green, and blue lines, respectively. The solid black line shows prediction of classical (non-quantum) thermodynamics for emission at 5000K (Figure source: Wikipedia.org).

The shape of the blackbody spectrum was measured in laboratory at the end of 19th century and was a source of much puzzlement to the physicists of that time because it contradicted the expectations of classical thermodynamics (the branch of physics studying heat and radiation). Attempts to understand the shape of the blackbody spectrum led to development of quantum mechanics. The formula accurately describing the shape of the measured spectrum was proposed by the German physicist Max Planck in 1900. Planck also showed how this shape can be understood using theoretical calculations based on concepts of quanta of energy and thermodynamic equilibrium. The Planck formula describing the shape of the blackbody spectrum as a function of wavelength λ is given by the following formula:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{\exp(\frac{hc}{\lambda kT}) - 1} \tag{1.2}$$

where $h = 6.63 \times 10^{-34}$ J/s is the Planck constant, $c = 2.99 \times 10^8$ m/s is the speed of light in vacuum, and $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant. The Planck spectrum shape for different temperatures along with predictions of the classical theory is shown in Fig. 1.1.

Fig. 1.2 shows the spectrum of the CMB radiation – a ubiquitous relic radiation from the first few thousand years in the existence of our universe. This radiation was emitted when the universe was very hot and dense and almost in thermodynamic equilibrium. The spectrum is thus very accurately approximated by the Planck formula. Note that this is yet another example of the amazing universality of physical laws in nature. You can use the same formula to describe the spectrum of a regular incandescent bulb and spectrum of relic radiation from the early era of evolution of our universe!

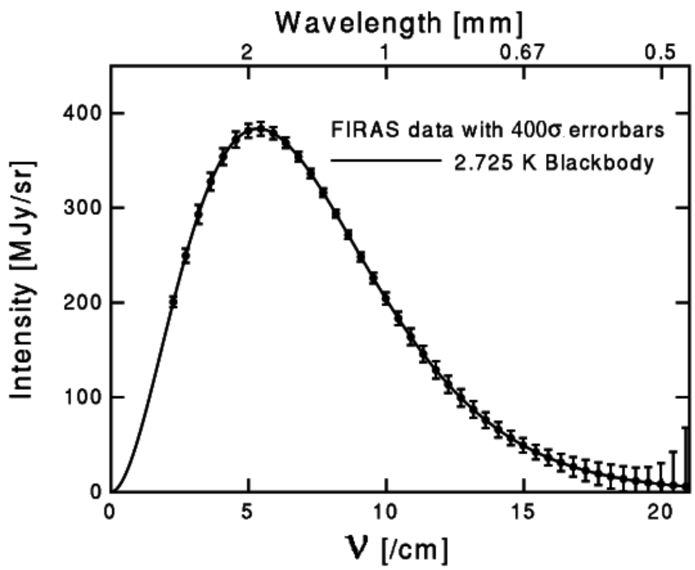

Figure 1.2: Spectrum of CMB as measured by the FIRAS instrument on COBE satellite in the 1990s. Note that the measured spectrum is described almost perfectly by the Planck formula with an effective temperature of 2.7K; the error bars shown are 400σ!

1.3 Experimental setup

Spectrometer hardware

In this lab we will use the the Ocean Optics digital spectrometer, which measures light in the range 350 to 1000 nm with a resolution of about 1 nm (1 nm = 10^{-9} m.) Light from the source under study is collected by an optical fiber. **IMPORTANT: the fiber is fragile, handle with care.** The fiber will be fixed in a holder, which can be adjusted to point to the light bulb. The spectrometer is connected to the computer through USB, and dedicated software (Spectra Suite) is used to operate the spectrometer and save the data. For reference, Fig. 1.3 shows the main controls of the SpectraSuite software.

You will use a regular 25W incandescent light bulb setup in a holder, with a voltage regulator to change the light intensity.

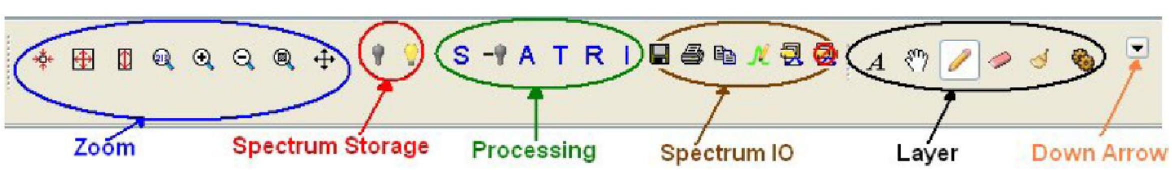

Figure 1.3: The Spectra Suite software controls: zoom controls can be used to zoom in and out the graph. The gray bulb records background ("dark") spectrum, while the yellow bulb records processed signal spectrum

Suggested procedure for saving spectra

For the following experiments, you can either work alone or in groups of 2. You'll need to operate the voltage control, run the Spectrum Suite software and copy the data and images into Excel and Word documents, and take notes. Please create a personal folder into which files can be saved, and delete it at the end of the day.

You're welcome to use the software of your choice when completing these assignments; e.g., Libre-Office, Python, or Matlab. But, in the past most students have found copying and pasting into Word and Excel to be easiest. To do this, we suggest open a Word and an Excel file in which you save your measured spectra at the beginning of your work.

To save an image of your graph, click on the third from right icon in the Spectrum IO controls (Fig. 1.3). This will copy image of the graph to the clipboard. Then, paste the image in the Word document by pressing Ctrl-V. To save the spectrum you measured in digital form as two columns of numbers, press the third icon from the left in the Spectrum IO controls (the icon showing two sheets of paper to the right of the printer icon), which will copy the digital spectrum into the clipboard. Now go to an Excel file and choose the column into which you want to paste your spectrum (usually column A, first row) and press Ctrl-V, which will paste the measured spectrum as two columns of numbers (wavelength in nm and counts for your spectrum) into the Excel worksheet.

At the end of the lab, save the Word and Excel files with images of graphs and numerical spectra and their analyses done during the lab on a USB stick or email copies to yourself.

An alternative, but slower, way to save the data is to click on the floppy disk icon in the Spectrum IO controls. The format must be "Tab delimiter, no header". The writing directory must be specified ("Browse" button). The spectrum is saved in a text file (.txt) as two columns, the first column giving the wavelength in nm, the second column the corresponding intensity. This file can be imported into an Excel worksheet using Open File within the File menu of Excel.

APPENDIX A

Lab Report Format

In a general sense, the labs should demonstrate Rubric Rows F1 and F2 (see Table **??**), in addition to the other rubric rows listed in the lab write-up.

A.1 General

- The report should be typed for ease of reading. Text should be double-spaced, and the page margins (including headers and footers) should be approximately 2.5 cm, for ease of marking by the grader. Each page should be numbered.
- The first page should include the title of the lab; lab section day, time, and number; and the names of the members of your lab team.
- If the rubric row refers to a particular part of your lab report, clearly label that part of the report with that rubric row. For example, you should label the section where you demonstrate uncertainty propagation with "G2" if that rubric row is being assessed in that lab.

A.2 Organizing the report

If the lab is clearly framed as an observational, testing, or application experiment, you can follow the corresponding rubric for the elements to include in the report (see, respectively, Rubrics B, C, and D in Appendix **??**).

In general, the report should include the following sections:

A.2.1. **Introduction.** A written description of what the lab is designed to investigate and a brief summary of the procedure used. This section should be at least a full paragraph long, and not more than 3 double-space pages.

You don't need to include too much detail here, but it should be a complete and concise description of the purpose and general method used in the lab. Imagine a classmate who hasn't seen the lab writeup asked you, "what is this lab about? What do you do?" You should be able to hand them your introduction, and they'd be able to understand the purpose and general structure of the lab. But you need not mention every step and calculation here.

A.2.2. **Analysis and discussion.** For most labs that have more than one part, this should be broken up into parts and labeled in order. This section must include all of the following, in the same order in which these elements appear in the lab instructions.

- Any data that you've collected: tables, figures, measured values, sketches. Whenever possible, include an estimate of the uncertainty of measured values.
- Any calculations that you perform using your data, and the final results of your calculation. Note that you must show your work in order to demonstrate to the grader that you have actually done it. Even if you're just plugging numbers into an equation, you should write down the equation and all the values that go into it. This includes calculating uncertainty and propagation of uncertainty.
- If you are using software to perform a calculation, you should explicitly record what you've done. For example, "Using Excel we fit a straight line to the velocity vs. time graph. The resulting equation is $v = (0.92\,\mathrm{m/s^2})t + 0.2\,\mathrm{m/s}$.
- Answers to any questions that appear in the lab handout.

A.2.3. **Conclusion.** This can be very short, and will generally only require one or two paragraphs. In your conclusion, you should summarize the point of the lab and what you learned, both in the frame of a scientist conducting the experiment ("What did the experiment tell us about the world?") and in the frame of a student ("What skills or mindsets did I learn?").

A.3 Graphs, Tables, and Figures

Any graph, table, or figure (a figure is any graphic, for example a sketch) should include a caption describing what it is about and what features are important, or any helpful orientation to it. The reader should be able to understand the basics of what a graph, table, or figure is saying and why it is important without referring to the text. For more examples, see any such element in this lab manual.

Each of these elements has some particular conventions.

Tables

A table is a way to represent tabular data in a quantitative, precise form. Each column in the table should have a heading that describes the quantity name and the unit abbreviation in parentheses. For example, if you are reporting distance in parsecs, then the column heading should be something like "distance (pc)". This way, when reporting the distance itself in the column, you do not need to list the unit with every number.

Graphs

A graph is a visual way of representing data. It is helpful for communicating a visual summary of the data and any patterns that are found.

The following are necessary elements of a graph of two-dimensional data (for example, distance vs. time, or current vs. voltage) presented in a scatter plot.

- **Proper axes.** The conventional way of reading a graph is to see how the variable on the vertical axis changes when the variable on the horizontal axis changes. If there are independent and dependent variables, then the independent variable should be along the horizontal axis.
- **Axis labels.** The axes should each be labeled with the quantity name and the unit abbreviation in parentheses. For example, if you are plotting distance in parsecs, then the axis label should be something like "distance (pc)".
- **Uncertainty bars.** If any quantities have an uncertainty, then these should be represented with so-called "error bars", along both axes if present. If the uncertainties are smaller than the symbol used for the data points, then this should be explained in the caption.