Astronomy 1 – Introductory Astronomy
Spring 2014

Lab 1: The Inverse Square Law of Light

Introduction

You know from everyday experience that lights look brighter when we are close to them and fainter when we are farther away, but you may not have thought about trying to quantify that relationship.

In astronomy, knowing this exact relationship can be a powerful tool – if we can recognize the intrinsic nature of a source (for example, determining from a star's spectrum that it is like the Sun and so should have the same energy output) then comparing its observed brightness to its intrinsic power output (what astronomers call *luminosity*) can give us the distance to the source.

As will happen repeatedly in your study of physics and astronomy, we must give a word that has an everyday meaning a more specific, quantitative definition. Specifically, *brightness* as used by physicists and astronomers is defined as the rate at which a light source delivers energy to a standard unit area of a sensor (like your eye, a camera, a telescope) – or energy per time (that's the rate) per area:

$$brightness = \frac{energy/time}{area} = \frac{power}{area} \quad \text{(SI units: Watts/m}^2\text{)}$$

Note that Joules are the SI units of energy and seconds the SI unit of time, and that Jouls/second (J/s) has a particular name, the Watt (W).

This week's lab has two goals: for you to determine experimentally how the brightness of a light source depends on distance from the source and also, in the process, to learn something about designing experiments. In particular, scientists always have to be concerned about how to measure what they are interested in while eliminating the effects of extraneous processes.

Your lab group will design an experiment to measure the distance dependence of the brightness of a light source, and then carry out the experiment, analyze the data, and improve and repeat the experiment as needed to identify the mathematical form of the distance dependence.

Now, we have a theoretical model for understanding the relationship among brightness, intrinsic power (luminosity), and distance – as described at the beginning of Ch. 15 (pp. 493 - 494). That model's quantitative prediction can be expressed mathematically as:

$$B = \frac{L}{4\pi d^2}$$

Make sure you understand what the symbols mean and what their units are.

Pre-lab questions

1. What are the names and units of *B*, *L*, and *d* and which one is directly measured and which one do we usually want to know in astronomy? And how do we deal with the third variable?
2. Explain in your own words and in just a couple of sentences how the inverse square law equation, above, is derived – what is its physical basis?
3. What are some of the assumptions and idealizations in the picture used to derive the inverse square law? You might ask yourself if the equation would be true for any light source at all. Like, what about a flashlight?

In order to experimentally determine the exact expression that relates *B*, *L*, and *d*, we'd need a detector that actually gives us a measurement in physical brightness units – in other words, we'd need our detectors to be calibrated, but they are not. They give readings in units of electric current, which are proportional to, but not equal to, brightness. So we can't hope to verify the "4π" and the "*L*" but we can determine the functional relationship between *B* and *d*: is *B* proportional to d^{-2}? How close is it to that? Can we rule out proportionality to d^{-1} or to d^{-3}?

The Experiment

Goal: Based on measurements your lab group designs and carries out, find a mathematical function describing the brightness of a light source as a function of distance.

Available equipment: A light bulb, a photodetector (sensor that measures total light energy per time, or power, reaching its surface), a two-meter-long ruler, a measuring tape, black paper and cardboard, tape, scissors. Your lab instructor will explain how to operate the photodetector and what its output means.

1. Plan an experiment to measure how the brightness of the light bulb depends on the distance from the light bulb.

As you and your partner/group plan your experiment, think about the following:

- What sources of light are there in the room other than coming *directly* from the light bulb?

- When scientists design an experiment, they must always figure out how to deal with unwanted contributions to their measurements (often referred to as "background"). Broadly speaking there are two ways to do this: by eliminating those unwanted contributions from the measurement itself, or by accounting for them in the analysis of the data.

  For example, when you are weighed at a visit to your doctor's office, the scale must be zeroed so that it reads zero when nothing is resting on it, and generally you are asked to take off your shoes and jackets or heavy sweaters so that these do not contribute their weight to the scale reading. But, if you left on your shoes for example while being weighed, their small contribution to your measured weight could be corrected for during the "data analysis" the doctor does by subtracting the known (or measured) weight of your shoes from the result registered on the scale.

  In this experiment and your subsequent analysis, how will you deal with background?

- When you measure the brightness at a certain distance, is there any advantage to making multiple measurements?
- How will you quantify the uncertainty on your measurements?

2. Discuss your experimental plan with your lab instructor. Refine your plan based on your discussion, and then in your lab notebooks briefly describe your experimental procedure, including a sketch of how the apparatus will be used. Your plan should include multiple measurements

3. Carry out your measurements and record your data.

   You may record your data directly into a spreadsheet on the computer (if so, be sure to save frequently!) and print out your finished data table to put in your notebook, or you may record your data in one person's notebook and then enter them on the computer.

   Record uncertainties as well as the data values themselves.

4. Make a plot of your corrected data, with error bars – Kaleidagraph is our standard tool – and after you've got a good looking graph, try making the axes logarithmic. Does the logarithmic axis plot have any advantages over the normal linear one in terms of revealing information about your data? Include at least one sentence in your lab write up discussing this issue.

5. Fit several different power-law models to your data: First, fit a power-law with the index forced to be -2, from our theoretical expectation. Print out your data plot with that model fit shown and include it in your lab write up. You should also fit a model where the power-law index is a free parameter. And then you should fit models where it's forced to be -1 and then -3. It's up to you how to show these fits (all on the same plot, separate plots, some combination; linear or log axes or both). Remember, your goal is to make an experimental determination of how brightness and distance are related and more quantitatively, to determine what range of power-law indices are compatible with your data.

Note that even in the case where you are fixing the power-law index at some value, you still have to perform a fit to find the value of the constant out front (and further note that that constant implicitly accounts for a lot of things: a conversion from electric current to brightness in the detector, the area of the detector, and the luminosity of the light bulb).

6. Write up your results in your lab notebook. Your write-up should include:

    a. The title of the lab, the date and your lab partner's name.
    b. A short, one paragraph introduction clearly stating the purpose of the lab with a very, very brief description of the methods you'll use to accomplish that purpose.
    c. A description of the procedure and apparatus set up you'll use to accomplish your goal. This doesn't have to be more than a few paragraphs long, but probably should include a sketch. A classmate who hasn't done the lab should be able to do it without help by reading your instructions.
    d. A data table (can be printed from Kaleidagraph; don't forget to label your columns).
    e. All relevant plots (with descriptions/explanations).
    f. A discussion of what your results mean. A good discussion will include an enumeration of sources of error and uncertainty and perhaps suggestions for reducing the error and uncertainty in some future, better experiment. In this particular lab, you should also address the issue of whether the actual luminosity (100 W vs. say 50 W) of your light bulb affects your results at all. And finally, assuming your best-fit power-law index deviates from -2 exactly because of imperfect estimate of the background levels, state whether the sense of the error is that you likely overestimated the background or underestimated it.
    g. A one paragraph conclusion, recapping the results of the lab (and goals achieved, or not). This should certainly include any quantitative results you find.

This will be the general structure of your lab write-ups throughout the semester, but the nature of the data tables and plots will vary, especially when we do our outdoor observing labs.