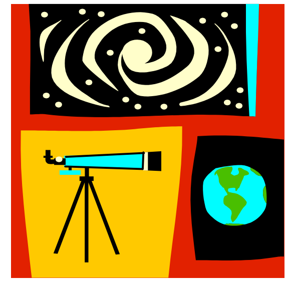
You Are the Spectrometer!
A Look Inside Astronomy's Essential Instrument
(Robert B. Friedman & Matthew K. Sharp)

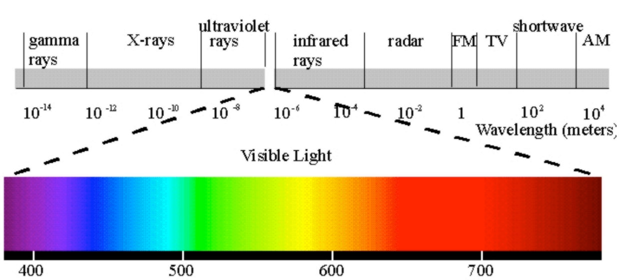


Introduction

Astronomy is a unique science because unlike many of the other sciences, the subjects of its study are mostly out of human reach. It is usually impossible for an astronomer or astrophysicist on Earth to recreate in their lab the objects about which he or she wants to learn. This difficulty makes the usual process of experimentation complicated. Since the astronomer cannot go to the object, the only thing left to do is observe it from afar with a telescope and a spectrometer. Astronomers collect the electromagnetic radiation that is emitted by all sorts of interesting objects, or sources, throughout the universe and investigate the properties of this radiation.

> *What are some of the properties of the objects an astronomer might be interested in and learn about by studying this radiation?*

The light we can see with our eyes from light bulbs, planets, stars, nebulae, galaxies or other sources is just a form of electromagnetic radiation like x-rays, gamma rays, radio waves or microwaves. What makes visible light from a light bulb different than the x-rays a doctor might use to see if you broke a bone is the **energy** of the radiation; x-ray radiation has more energy than visible light. This is also why x-rays can be dangerous to people. The ordering of radiation from the least energetic to the most is called the **electromagnetic spectrum.** The part of the electromagnetic spectrum where visible light belongs is called the **visible spectrum**. The visible spectrum is something you are very familiar with: it is the rainbow of colors. Blue/violet light is the most energetic, while red is the least.



Do you think radio waves or x-rays have more energy? Why?

You may already know that light is what transports energy from one place to another in the form of waves or particles called a **photons**. Just like you can transport the energy in your arm across a field by throwing a ball, a star can transport its energy by giving off light. A star or any radiating source in space can give off many types of radiation (light) with different energies. Finding out what types of radiation a source is giving off can tell us a lot about it. Looking at the distribution of radiation from an object is referred to as analyzing its spectra. A spectrometer records the spectrum of radiation coming from some source.

In what part of the visible spectrum (what color) do you think the sun is the brightest?

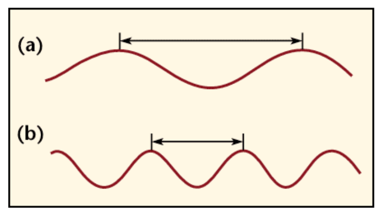
When you throw a ball, many things can happen. Someone can hit it with a bat, kick it with their foot, catch it and then pass it along to someone else, or run with it and score a touchdown. In the same way as you do with the ball, atoms of different elements also interact with the photons of light, intercepting them and then passing them along to another atom. In fact, elements only interact with light or radiation of specific energies. While hydrogen might interact with radiation of one energy, helium or carbon might not. This is similar to how a baseball player catches and hits baseballs, but wouldn't do anything with a football or a soccer ball. Since atoms of elements interact with photons of a particular energy, their influence will be present in the spectrum of radiation produced by any object containing that type of atom. Studying the spectrum of a source of radiation can tell us about which elements it is made of.

You will discover:

- How astronomers use lenses and mirrors to make images of distant objects.
- How a diffraction grating can separate light into its spectrum.
- How to use an optical system and a diffraction grating to analyze visible spectra.
- How to use what we learn to make an image of the Sun and study its visible spectrum.
- How to tell what the Sun is made of by comparing its spectrum with those of known elements.

Electromagnetic Radiation: All matter in the universe, even your body, emits electromagnetic radiation, or EM for short. The hotter matter is, the more radiation it can produce. Not only that, but hotter matter can also produce more energetic radiation. Your body emits small amounts of mainly **infrared** radiation that our eyes cannot see, while the sun emits great amounts of mainly visible light (that we can see). EM radiation can be thought of as a wave of electric and magnetic energy passing through space. These waves are similar to those you might think of in water, bobbing up and down, except unlike water waves these waves can travel everywhere freely, even through empty space. Since they are similar to water waves, we can measure their **wavelength**. A wavelength is the distance from one high point in a wave, also called a **crest**, to another (or from one low point, or **trough** to another). The smaller the wavelength of an EM radiation wave the more energy it has.

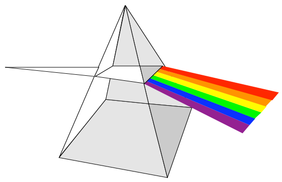
Which wave pictured to the right has the longer wavelength, a or b? Which has more energy?



Spectra and Spectrometers: The full electromagnetic spectrum of radiation ranges from low-energy, long wavelength radio waves to very high-energy, short wavelength gamma rays. Our eyes are sensitive to a very narrow range of wavelengths between 400-800 nm (nm stands for **nanometers**, a <u>billionth</u> of a meter!). We call this the *visible spectrum* since we can see it.

What is the wavelength of red light? Blue light?

The "white light" we see coming from light bulbs and the sun is really a combination of the full visible spectrum. When our eyes see the light of all these colors at once it appears the light is white. So how do we separate the combined white (or any color) light into its building block colors, or spectrum? This separation is the purpose of instruments such as **prisms** or **diffraction gratings**.



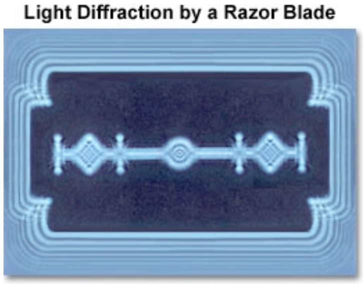
Prisms are usually triangularly shaped pieces of glass. When light passes from one material to another, it can be bent and change the direction of its path (think about when you put something under water and it looks distorted).

What are the two materials between which light is passing in the case of a prism?

The amount by which the path of light is distorted depends on its wavelength or energy. So light of different energies, or wavelengths, is bent into different directions. Since the different colors go different directions, they become separated from each other and we are able to see the rainbow spectrum of white light.

What color do you think an object that emits only blue and yellow light would appear?

Light Diffraction by a Razor Blade



Diffraction gratings are more complicated but more widely used in astronomy. As when it passes between two different materials, the path of light can also be changed by a sharp edge. Light passing a razor blade can bend around the sharp edge just as it bends when passing from air to glass.

Diffraction gratings are either mirrors or pieces of glass with many small edges cut into them, like a microscopic version of window blinds. When the light passes through the grating, it is bent in just the right way so as to separate the different colors, just like with the prism. A typical diffraction grating can have several thousand such edges cut out per millimeter. An astronomer would use a telescope to collect light from far-away sources, and then send that light through a diffraction grating to split the light into its spectrum. In this way astronomers analyze the spectra of distant objects like galaxies!

Source
http://skyserver.sdss.org/dr1/en/tools/places/page1.asp

You Are the Spectrometer!: Procedure

Part I: Exploring Prisms, Diffraction Gratings and Lenses

A. Lasers

- In a darkened room place a prism on the optical bench so that you can shine a light into it (it may take some playing around to figure out the right orientation to make it work).
- Shine a red laser beam through it, and note where it lands.

    1. *What is the wavelength (nm) of the red laser?*

- Now try shining a green laser from the same place.

    2. *Where does it land?*
    3. *What is the wavelength (nm) of the green laser?*
    4. *Where do you think a yellow laser would land? A blue one?*

- *Sketch your experimental set-up and the light paths of the two lasers.*
- Now switch to a transmission diffraction grating.
- Repeat the process of shining the differently colored lasers on the transmission diffraction grating. Record your observations in words and with pictures.

    5. *What is the difference between the laser light after it passes through the grating and the prism?*

- Now switch to a reflection diffraction grating. It works in the same way as the transmission grating, but it bounces the light backwards instead of allowing it to continue forwards.
- Repeat the process of shining the different colored lasers on the reflection diffraction grating.
- Mark the locations and colors of the diffracted laser light on a piece of paper behind the reflection diffraction grating. *Be very careful to keep the grating and the marking paper in the same location for both the lasers.*

B. White Light

- Now turn on a bright flashlight.

    6. *What do you think will happen when you shine the bright "white" light on the reflection diffraction grating?*
    7. *What colors will you see?*

8. Where will they be, compared to the spots from the lasers?

- Shine the “white” flashlight light on the grating. Make sure that the grating and paper are in the same location from the previous step.

(You know the wavelengths of the red and green lasers from before.)

9. *From the white light results, can you guess the wavelength of violet light?*

C. Lenses

- Select a lens from the lenses box.
- Place the lens above this paper and look through it to read the small sentence below.

********* The lens used this way works like a magnifying lens a detective would use to look for clues! **********

- With a black marker, draw a small stick figure on a piece of paper, and then cut the paper to fit over the flashlight. Tape it onto the flashlight.
- Place a screen or board on your table and shine the flashlight on it.
- Now hold the lens between the flashlight and the screen and attempt to focus an image of the stick figure onto the screen or board by moving the lens slowly back and forth between the stick figure and the screen.

10. Is the image right side up or upside down?

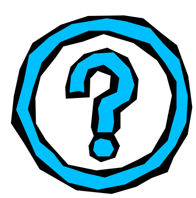
We call the three components of this optical system the **image**, **lens** and **object**.

- Experiment with your lens: try changing the distance between the 3 components of the system (the image, lens and object).
- Measure the size of the image and the two distances (between the object and lens and between the lens and the image) with a ruler each time you focus the image.

Record your measurements in your lab notebook.

11. Do the sizes of the images change?

12. Which configuration works best?



Part II: Exploring Sunlight

This part of the lab requires cooperation between everyone in the class. Using what we have learned about lenses in the previous section, we will assemble an optical system that we will use to make an image of the sun. In addition to the one lens in the previous section, we will need some additional equipment.

You may have noticed that if you moved the flashlight further from the lens the image comes into focus closer to the lens and is smaller in size. Since the sun is so very far away, its image formed by a lens will be very small and close to the **focal point** (the focal point is the closest a lens can possibly image an object and is located at the **focal length** from the lens along the axis that the light travels). Because a small image of the sun would be difficult to see on a screen, we will use an additional lens as a magnifier to enlarge the image produced by the first lens. This lens works just like a magnifying lens that people might use to read small print, which you did before. We will place the lens so that sunlight coming through the larger primary lens passes through this additional lens and is magnified. We can adjust the second, magnifying lens to focus an image at any distance.

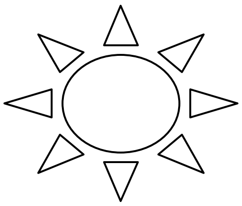
Besides lenses, we will also need to use a few mirrors mainly because we are inside and the sun is outside. The mirrors will direct the sunlight into our room by bouncing the light around. Since the sun is moving through the sky we need a way to make sure it is always in view of one of the mirrors. For this purpose we have a device called a **heliostat**. This is simply a fancy way of saying a mirror with a motor on it that can keep turning to stay facing the sun during the day.

!!! WARNING !!!

For the following experiment we will be working with sunlight. The sun is a very bright source of light and can be very dangerous to your eyes. Focused sunlight can also be very hot and may light things on fire.

DO NOT STARE DIRECTLY AT THE SUN!
DO NOT LOOK INTO THE LENSES AT ANY TIME WE ARE USING SUNLIGHT!
DO NOT POINT THE BEAMS OF LIGHT AT OTHER PEOPLE!
DO NOT LEAVE FLAMABLE MATERIALS IN THE FOCAL POINT OF THE LENS!

A. Imaging the Sun



- Position the heliostat in a window with the screw facing north. Loosen the screw that locks the mirror in place and then rotate the mirror to the desired position (e.g., so that the sunlight is reflected on the other mirrors you have set up.) Tighten the screw to set it.
- Since the location of the heliostat may not be convenient, we will use a free flat mirror to pipe the sunlight into our lab in the direction of our optical setup. Adjust the position of a second mirror to beam the light indoors. (This will be tricky.)
- It may be necessary to position a second or third flat mirror to fine-tune the location and direction of our beam of sunlight.
- Now place the first lens in front of the last mirror. For this we would like to use a lens that is as large in diameter as our beam of sunlight so we don't waste or lose any of it.

13. Where is the focal point of this lens? How can you tell?

14. How big is the image of the sun?

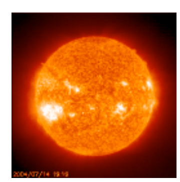
- Now we will use a second lens to magnify the image of the sun. This lens does not have to be as big because the image of the sun from the first lens is now quite small. Place the second lens so that it catches the light from the large primary lens and magnifies it.
- Adjust the position of the second lens to focus the image of the sun.

15. Sketch a diagram of this optical system. Make sure to include each component and label them with notes about their role in the system.

16. What happens when you move the second lens closer and further from the first?

17. Can you manage to image any other objects besides the sun?

18. What features can you identify in the sun?

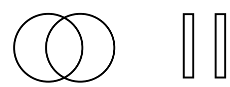


B. The Solar Spectrum

Now that we have the light from the sun where we want it to be (in our dark laboratory), we are ready to use the diffraction grating we used before to look at what colors are in the light from the sun. That is, we are ready to study the solar spectrum.

19. What was the color of the image of the sun you made in the previous section?

We want to make sure that we are only looking at light from the sun and not the rest of the room, so we will use a thin slit to block out “stray” light and select only the light from the image of the sun. Astronomers use slits to pick out a particular portion of an object. More importantly, slits help separate the colors in a spectrum. A grating separates an image into its spectral colors by producing a copy of the image for each color in the spectrum. (You may have seen this already in the “Seeing is Believing” night lab.) As an example, imagine the sun only produced blue and yellow light. The image of the sun would then appear to be greenish in color. If we shined an image of the full round sun onto the reflection grating, the grating would bounce back two copies of the round sun (one for each color), one blue and one yellow. Now imagine that these two circles overlapped on our screen. At the point of their overlap, the yellow and blue colors would mix together again and form a greenish region, which would be misleading. To make sure this doesn’t happen, we use the slit. Since the slit is thin, the different colored copies of its image will not overlap. This behavior will be a little more obvious after some experimenting.



- Position a reflection diffraction grating at the end of our optical system, after the last lens, so that we are shining an image of the sun onto it.
- Locate the spectrum of the sun with a piece of paper. This will be similar to what you did before with the lasers and flashlights.
- Try to adjust the position of the last lens to bring the spectrum into focus as you did with your images in the previous sections.

20. How does this spectrum look? In your lab notebook describe the following:

a. which colors can you see?

b. does it appear to be a perfect rainbow?

c. do you expect it to be a perfect rainbow? why or why not?

d. how does it compare to the white light from before?

- Remove the reflection grating and focus the sun onto the screen again.
- Put a thin slit between the two lenses.

21. Now what does the image look like on a screen?

22. Where can we put the slit so that it lets through the greatest amount of light from the sun?

- Install the reflection grating again. Use a piece of paper to see what colors are coming out.

23. What colors can you see now?

24. How does this spectrum compare to the colors of the spectrum without the slit?

- Play with the focus by moving the smaller lens back and forth. Have someone stand very close to the paper with the light on it while someone else tries to move the small lens back and forth until the details of the spectrum come into focus.
- With the better image created by using the slit, you should be able to see some unusual features in the solar spectrum. Instead of being a continuous rainbow as one might expect, there are a number of thin dark lines scattered throughout the spectrum. These are perhaps the most important features in the solar spectrum, and are called **absorption lines.**

24. How many lines do you see?

25. Draw a sketch of the lines in your notebook and take some notes. What colors of the rainbow are they located in? Are they all the same width and darkness?

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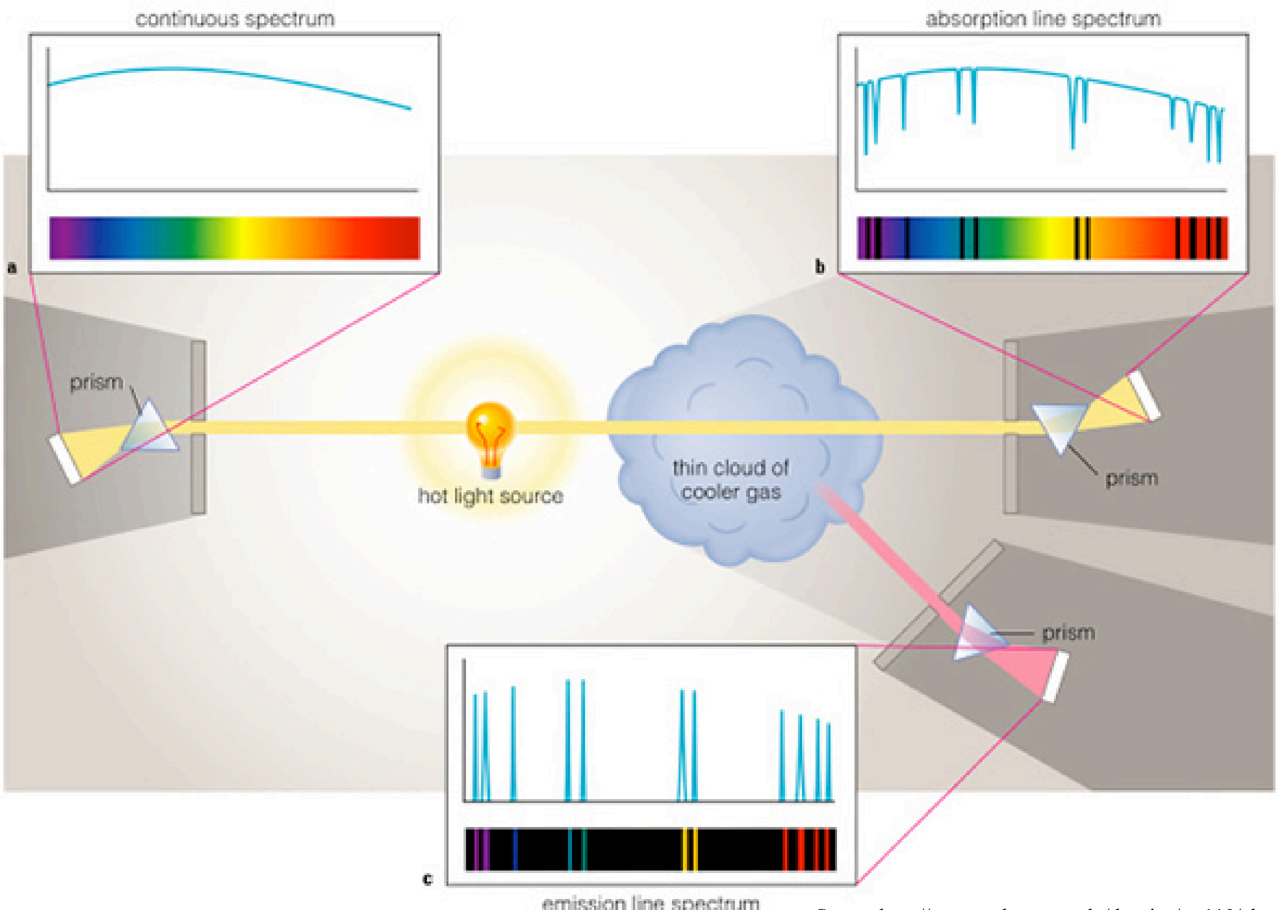
Part III: **<u>Exploring Line Spectra</u>**

You have already read in the introduction that different elements are able to interact with radiation that is of a specific energy or wavelength. If light with a continuous spectrum (perfect rainbow) passes through a cold gas composed of a certain element, that element can catch radiation at its special energy and prevent it from passing freely through the gas like the rest of the light. When we observe the spectrum of the light that has passed through this gas, we find that there are locations in the spectra that are missing light. For instance, hydrogen gas is sensitive to light in the red portion of the spectrum. Shining white light through cold hydrogen gas results in a rainbow missing a portion of its red light. This is the origin of the absorption lines that we were able to see in the solar spectra.

The reverse process occurs when a gas of any element is heated. In this case, gas is not blocking radiation but instead is generating it. For the same reasons that elements only absorb certain energies of radiation, they will also only emit those energies. For this reason the spectrum of radiation coming from a heated gas will produce distinct colors instead of a rainbow.



Source http://ganymede.nmsu.edu/tharriso/ast110/class13.html

Now that we have seen the spectrum of the sun, let's investigate what the absorption lines can tell us about the elements that make it up. To do this we will want to compare the spectra of elements we have in the lab to the spectrum of the sun and see if we can identify any matching features. To do this we will use what are commonly called **discharge tubes**. These are glass tubes filled with gas of one element. An electric current is passed through the tube, and caused the gas to shine. The tubes are not as bright as the sun is, so we will have to alter our setup to make their spectra more easily observed.

A. Camera and Projector Setup

We want to compare the dim discharge tubes to the sunlight. Since the camera is sensitive, it may be damaged by direct sunlight. So, instead of using the heliostat to look directly at the sun, we will point the mirrors so that they are looking at the sky nearby the sun. The light is the same, but it isn't as bright so it is safe to use with the camera.

- Remove the second magnifying lens and shine the light from the big lens through the slit and onto the diffraction grating directly.

> *25. Can you see anything on the sheet where the sun was projecting its light before?*

- Move your eye close to the diffraction grating.

> *26. Can you see the light from the slit in the diffraction grating?*
>
> *27. If you move from side to side, can you see other colors?*

- Setup a camera on a tripod, so that the camera lens is looking directly at the diffraction grating at about the same position where the student was able to see colored lines.
- The camera will be set up so that pictures can be taken and displayed from a computer, which will project the image onto a paper screen.
- One student should operate the camera and another the computer.

!!! HARD !!!

- The camera operator must adjust the focus and location of the camera until pictures show the lines of the spectrum.
- Try to make it so that ALL lines of the spectrum are visible at once.

> *28. Does the spectrum look the same this way as it looked before to your eye? Write three sentences comparing this spectrum to the drawing of the solar spectrum you made in the morning.*

- Using the markers provided, draw lines on the paper beneath the projection of the spectrum at the locations of the absorption lines in the spectrum [**DO NOT DRAW on the SCREEN**]. Use colors which correspond to the light which would be there if it wasn't being absorbed.

B. Discharge Tubes

Now that we can see the solar spectrum with the camera, let's look at some other sources of light for comparison. We will now use discharge tubes and special gas lamps.

- Block the light from the mirrors so that it doesn't shine on the slit anymore. Try not to move anything, because we might need it later and don't want to start over!

- Position the first discharge tube in front of the slit. Be careful to make sure that it lines up with and shines through the slit.

> *29. If you take another picture with the camera, what do you see? Draw it in your notebook. Note what element it is and what color the lines are. Can you guess what wavelengths they have?*

- With the markers, draw colored lines at the location of the lines on the paper. This time the lines are emission lines, so the proper color is obvious.

- Now replace the first tube with a second one in front of the slit so that it lines up and shines through it again.

> *30. If you take another picture with the camera, what do you see? Draw it in your notebook. Note what element it is and what color the lines are. Can you guess what wavelengths they have?*

- With the markers, draw colored lines at the location of the lines on the screen.

Continue the above procedure for all of the discharge tubes and gas lamps. It should be clear by now that every element has a different set of lines in its spectrum, like a fingerprint. We can use the elements' spectral fingerprints to identify them from their effects in radiation. When we are finished we will have a collection of these fingerprints on the computer, in your lab notebooks, and from the lines we marked on the screen. Using these fingerprints and our solar spectrum we can now identify which elements are in the sun.