

# INSIDE LAB 7: Measuring the Velocities of Stars

**OBJECTIVE:** To understand how the Doppler shift allows us to measure the velocities of stars towards or away from us.

## DISCUSSION:

One of the best ways to understand stars is to look at their spectra. The spectrum of a star is a plot of the intensity of the light coming from that star as a function of wavelength. Although we like to pretend that stellar spectra are simply block body distributions, the reality is far more complex. Consider, for example, the spectrum in Fig. 1, showing the actual spectrum of a star. The intensity is not a smooth curve at all, but has innumerable bumps and wiggles. What is causing all of these minute features?

Though there are many contributing factors, one of the most important is *absorption lines*. Absorption lines are caused by cool atoms in the atmosphere of the star that preferentially absorb particular wavelengths, causing a decrease in the intensity at that wavelength. For example, in the spectrum shown, there is a clear dip in the spectrum around a wavelength of 590 nm. This dip is caused by sodium, which absorbs light in this region of the spectrum.

Let's focus in more closely on this region to get a better sense of what is going on. Fig. 2 shows the actual spectrum of our Sun in the region around 590 nm. It is clear that, in fact, there is not one, but two distinct dips in the spectrum caused by sodium atoms. These occur at wavelengths of  $\lambda_{a0} = 588.995$  nm and  $\lambda_{b0} = 589.5924$  nm respectively. The other, smaller dips in the spectrum are caused primarily by absorption in Earth's atmosphere, and do not interest us.

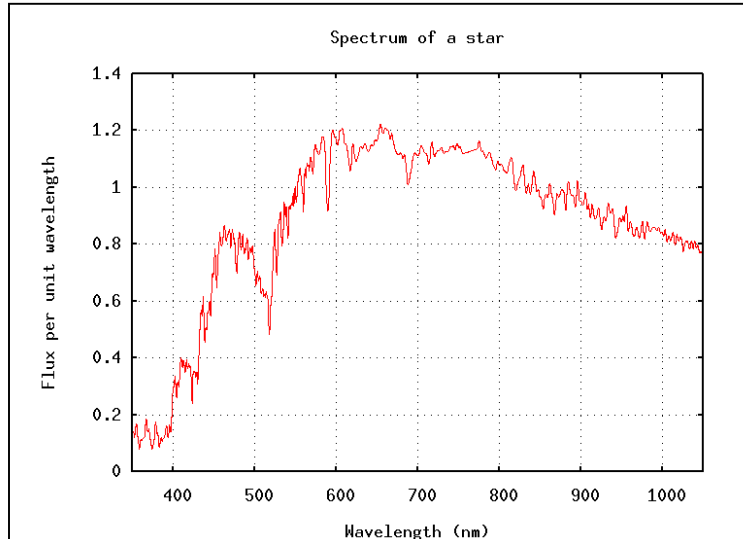


Figure 1: The spectrum coming from a typical star.

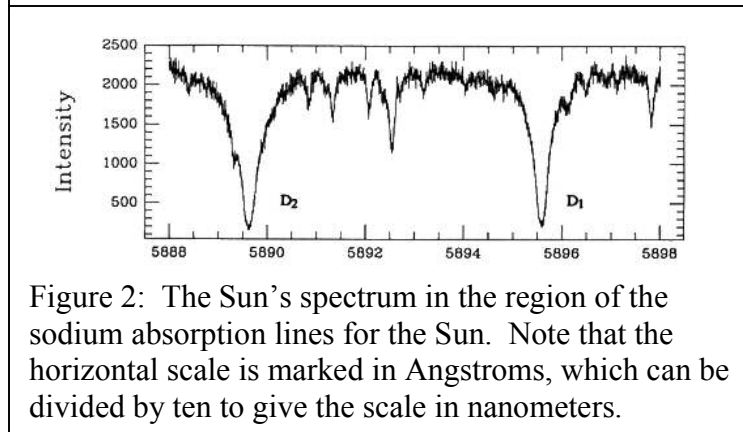


Figure 2: The Sun's spectrum in the region of the sodium absorption lines for the Sun. Note that the horizontal scale is marked in Angstroms, which can be divided by ten to give the scale in nanometers.

To simplify things, we will use as our reference not an actual solar spectrum given in Fig. 2, but a simplified spectrum that shows just the effects of the sodium lines, as illustrated in Fig. 3. The two lines from sodium clearly stand out, and their wavelengths are easily identified from the position of the minima. The presence of these dips in the spectrum clearly indicate the presence of sodium in the Sun's atmosphere. The exact *shape* of these absorption features can give additional information, such as the amount of sodium, the pressure of the gas, the temperature of the star, and even the rotation of the star. But none of these factors change the *wavelength* of these spectral features.

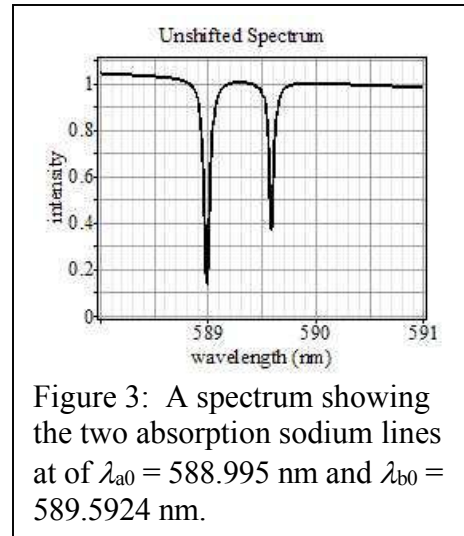


Figure 3: A spectrum showing the two absorption sodium lines at of  $\lambda_{a0} = 588.995$  nm and  $\lambda_{b0} = 589.5924$  nm.

There is one thing that *can* affect the wavelength. A star moving towards or away from has, due to the Doppler shift, all of its waves shifted to shorter or longer wavelengths, as illustrated in Fig. 4. Moving objects generate waves of any type (including light) which is shifted to shorter or longer wavelengths. An object moving towards you has its wavelength shifted to shorter wavelengths, in a phenomenon called *blue shift*, while an object moving away has its wavelength shifted towards longer wavelengths, which is called *red shift*. The new wavelength  $\lambda$  is related to the unshifted wavelength  $\lambda_0$  by the formula

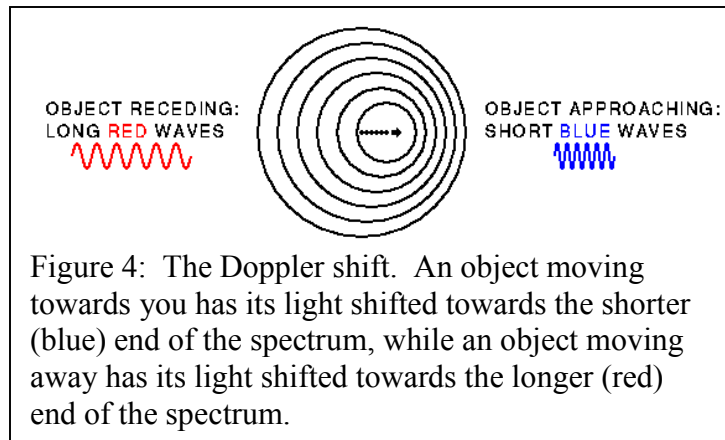


Figure 4: The Doppler shift. An object moving towards you has its light shifted towards the shorter (blue) end of the spectrum, while an object moving away has its light shifted towards the longer (red) end of the spectrum.

$$\frac{v_r}{c} = \frac{\lambda - \lambda_0}{\lambda_0}, \quad (1)$$

Where  $v_r$  is the velocity of the source away from you, and  $c = 300,000$  km/s is the speed of light. If an object is moving towards you, you can still use this formula, but then  $v_r$  will come out negative.

For example, suppose the spectrum of a particular star in the neighborhood of the sodium lines was as appears in Fig. 5. We note still the presence of the two sodium absorption lines, but they have shifted to a higher wavelength. This demonstrates that this star is moving away from

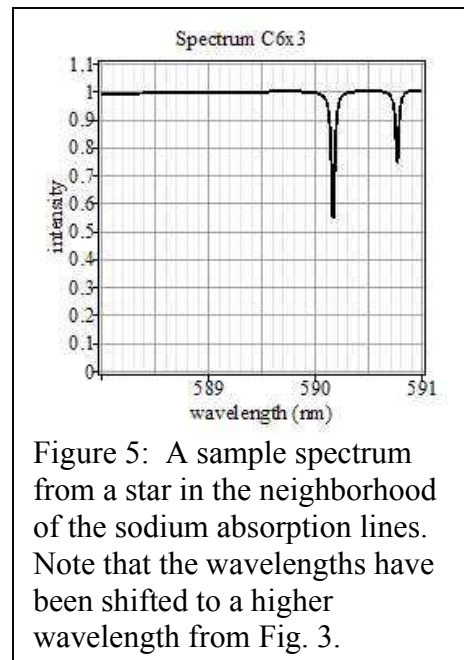


Figure 5: A sample spectrum from a star in the neighborhood of the sodium absorption lines. Note that the wavelengths have been shifted to a higher wavelength from Fig. 3.

you. One can see, for example, that the shorter wavelength of the two lines has shifted to approximately  $\lambda_a = 590.18$  nm. By comparing this with the unperturbed wavelength, we can then estimate the velocity of this star, namely

$$\frac{v_r}{c} = \frac{\lambda_a - \lambda_{a0}}{\lambda_{a0}} = \frac{590.18 - 588.9950}{588.9950} = 0.00201,$$

$$v_r = 0.00201c = (0.00201)(300,000 \text{ km/s}) = 603 \text{ km/s}.$$

Since the result came out positive, we know that this star is moving away from us, at about 603 km/s. We could then verify the speed using the second spectral line in a very similar way.

In this lab, you will examine several stellar spectra in the neighborhood of the sodium absorption feature. By measuring the position of the spectral lines, you will then perform a measurement of the hypothetical star.

### EXERCISES:

Your TA will distribute to you a set of (artificial generated) stellar spectra in the neighborhood of the sodium absorption feature. Your job is to determine the velocity of the star. In each case, you will do so twice, using the position of each of the two absorption lines.

#### EXERCISE 1:

Look at the first of the six spectra your TA has given you. Record the name of the spectrum in the first column of the table below

#### EXERCISE 2:

As carefully as possible, measure the position of the first sodium spectral line, in nm. Wavelength  $\lambda_a$  will always be the lower frequency (leftmost) of the two dips. Repeat for the second absorption line,  $\lambda_b$

#### EXERCISE 3:

Calculate the velocity of the star using the formula

$$\frac{v_a}{c} = \frac{\lambda_a - \lambda_{a0}}{\lambda_{a0}},$$

Where  $\lambda_{a0} = 588.9950$  nm, and the speed of light is  $c = 300,000$  km/s. Round it off to the nearest km/s. Repeat using  $\lambda_{b0} = 589.5924$  nm. Record both velocities.

#### EXERCISE 4:

The two velocities you found in exercise 3 *should* be the same. Average them to get your best estimate of the velocity of this star. Take the absolute value of the difference,  $\Delta = |v_a - v_b|$ . This gives you an estimate of how much you have misestimated the speed of the star.

Spectrum Name	$\lambda_a$ (nm)	$\lambda_b$ (nm)	$v_a$ (km/s)	$v_b$ (km/s)	$v_{ave}$ (km/s)	$\Delta$ (km/s)

Useful formulas:

$$\frac{v_r}{c} = \frac{\lambda - \lambda_0}{\lambda_0}, \quad c = 300,000 \text{ km/s}, \quad \lambda_{a0} = 588.9950 \text{ nm}, \quad \lambda_{b0} = 589.5924 \text{ nm}.$$

EXERCISE 5:

Repeat exercises 1-4 for the five remaining spectra. Record your answers in the table above.

EXERCISE 6:

Look at the final column of your table. Average these six numbers to get a typical error. What do you think is the source of this error? What could make this error smaller?

Typical Error = \_\_\_\_\_ km/s

Probable source of error/suggestions for making it smaller:

EXERCISE 7:

Which of the six spectra are from stars that you think are moving away from you? Which are moving towards you? Are there any for which, due to errors or uncertainty, you aren't sure about? Write your answer below.