

Measuring the Doppler Shift of a Kepler Star with a Planet

1 Introduction

The Doppler shift of a spectrum reveals the line-of-sight component of the velocity vector (“radial velocity”) of the object. Doppler shifts can be measured from spectral lines in emission or absorption at all wavelengths of the electromagnetic spectrum. Doppler shifts are commonly measured to determine the radial velocities of planets, stars, interstellar gas, and galaxies. In this lab you will measure the Doppler shift of a star that has never had its radial velocity measured. You will be the first to measure it.

2 Overview of the Doppler-shift Project

Last year, NASA launched a new telescope into space called the *Kepler* Space Telescope designed to detect the first Earth-sized planets ever discovered.

http://www.nasa.gov/mission_pages/kepler/main/index.html

The Kepler telescope takes images of the sky near the Cygnus constellation, measuring the brightnesses of 100,000 stars every 30 minutes, trying to find stars that dim repeatedly. Such repeated dimming is a tell-tale sign of an unseen planet that crosses in front of the star every orbital period (we will attempt to detect such a phenomenon in the next lab). The *Kepler* telescope has now found many such stars that show dimming due to probable planets orbiting them. Your project is to measure the Doppler shift of one of these host stars found by *Kepler*. These discoveries will be made public February 2011, so you will be the first to measure the Doppler shift of the star you observe.

You will obtain a spectrum of a *Kepler* star using the Lick Observatory 3-meter telescope and its high resolution spectrometer, the “Hamilton”

spectrometer. This spectrometer is similar to the USB2000 spectrometer you already used. But this spectrometer captures many spectral orders, of which you will be using just one (for now). At the back of the spectrometer is a CCD that detects the spectrum, with each pixel sensing the photons from a different wavelength. As with the USB2000 spectrometer, the Hamilton spectrometer causes increasing wavelengths of light to hit along the length of the CCD. But this CCD has two dimensions (rows and columns, like a two dimensional array), and the spectrum of light hitting the CCD has some width as well as length.

In this project, you will measure the Doppler shift of the famous two spectral lines from sodium atoms the “Sodium D lines” (look this up in Google). These two spectral lines are caused by the absorption of light by sodium atoms in the atmosphere of the star. Those two absorption lines are very deep, making the spectrum almost black at the central wavelengths of the two lines. These two sodium lines are strong in stars of spectral type F, G, and K, because their photospheres have temperatures of 7000 - 5000 K, leaving sodium neutral rather than ionized. These two deep spectral lines allow you to accurately measure their Doppler shift.

For the wavelength calibration, you will use emission of the sodium D lines by the sodium street lamps in San Jose (30 miles from Lick Observatory). Those sodium lamps shine on the night sky, and the light scatters off the air molecules and into the 3-meter telescope at Lick Observatory. Normally this is unwanted “light pollution”, but in this project you will use those two sodium D emission lines to determine the wavelength calibration for the spectrum in the vicinity of those lines. As there are only two sodium D lines, you will construct only a linear wavelength calibration, by measuring the pixels at which the two emission lines occur.

3 Taking the Spectrum and Reducing the Raw CCD Image

You will use the “Remote Observing Facility” in Campbell hall (room 11, Campbell Hall) to take your spectrum of a Kepler star. Howard Isaacson will be there to help you take the spectrum, store it as a “FITS” file, and ftp it to the ugastro computer cluster. You must also ask Howard Isaacson for a

"flat-field" exposure that he took earlier. This is a spectrum of an ordinary incandescent lamp that emits the Planck function, i.e. a continuous, smooth distribution of light at all wavelengths. Your group will all analyze the same stellar spectrum, giving you a chance to work with them and compare your final radial velocities.

To prepare for this lab, open a new directory:

```
mkdir doppler
```

and then "cd" to that directory. You should write IDL code that reads your raw CCD image, storing it as a variable. One way to read a FITS image is using the routine, "mrdfits":

```
filename = 'w14.nnn.fits'  
im = mrdfits(filename,/fscale)
```

Here, the values of "w14" and for "nnn" will be those for your CCD image. You can display your image by using the "display" command:

```
display,im
```

or, to specify the brightest and faintest levels of "gray scale":

```
display,im,min=460,max = 3000
```

You can vary the min and max levels to change the gray scale to taste. You should see many nearly horizontal stripes, each being a different spectral order from the Hamilton spectrometer. You should then extract a rectangular portion of that image that surrounds the sodium D lines. They are located in the image between columns 865:1150 and between rows 552:574. You may want to use this command to establish a rectangular cut-out in that region:

```
sub_im = im(865:1150,551:575)
```

Use the "display" to see that region on the computer screen. You should see a strip running from left to right and slightly upward. That is the spectrum, with each pixel containing the number of photons that hit it. Notice

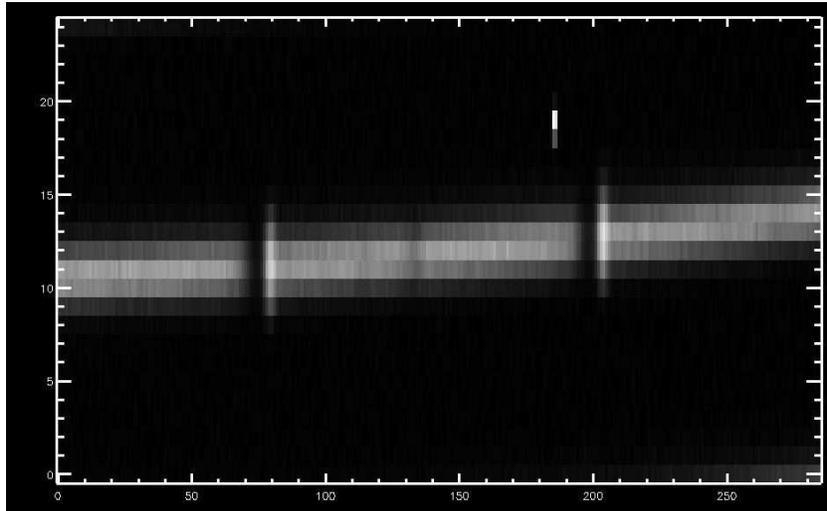


Figure 1: Zoom of an Hamilton spectrum centered on the two sodium D lines. The dispersion direction runs from left to right (wavelength increases in that direction) and the spectra are slightly tilted with respect to being perfectly horizontal. The bright spot at pixel (185,19) is either a so-called “hot” pixel or the impact of a cosmic ray on the detector during the integration.

that the spectrum has some width along the direction perpendicular to the spectral dispersion (see Figure 1).

Now, also cut-out the same region in the “flat-field” exposure of the incandescent lamp.

3.1 Subtracting the Dark Counts, Flat-fielding and Extracting the Spectrum

CCD cameras, just like the PMT we worked with in Lab 1, have non-zero rate of “dark counts”, and further have a “bias” level set for every single exposure. You should subtract both the dark counts and bias level from your cut-out image. The dark counts and bias counts can be estimated from the pixels above and below the spectrum (see Figure 1). The easiest way to measure the total dark plus bias counts is to simply determine the median value of your image, which will have a value near the counts in the large number of pixels that received no light (what assumption is made here?).

Then subtract that dark and bias background level.

```
dark_and_bias = median(im)
im = im - dark_and_bias
```

Each pixel has a different sensitivity to photons called "quantum efficiency", or "QE" for short. To remove the effects of these QE differences you should divide your stellar spectrum by the flat-field exposure. That flat-field exposure has counts in each pixel proportional to those same QE differences from pixel to pixel (what assumption is made here?). By dividing, you remove the QE effects in your stellar spectrum. Before dividing by the flat-field exposure, first "normalize" it by dividing the entire image by the median value in that cut-out flat-field image:

```
flat_im = flat_im/median(flat_im)
```

Now perform the flat-fielding by dividing the stellar spectrum cut-out by that normalized flat-field image. The result is an image of the spectrum that has the pixel-to-pixel differences in QE removed.

Now you will "extract" the spectrum, by adding up the counts in the pixels within each column, all of which detected the same wavelength. Write a little code to add up the counts along the columns, leaving a one-dimensional (1-D) spectrum. This is a 1-D spectrum just as the USB2000 spectrometer gave you.

3.2 Wavelength calibration

Display your 1-D spectrum. Do you see with just your eyes the Doppler shift of the stellar absorption lines relative to the emission lines? Is the star approaching us or receding?

You need to determine the wavelength of each pixel along the spectrum, i.e. "wavelength calibration" $\lambda(x)$, just as you did with the USB2000. But here you will use the known (laboratory) wavelengths of the sodium D lines emission lines that you see in the spectrum. Write code, similar to what you did before with the mercury (Hg) emission lines, finding the centroids

or the peak pixel position of both sodium D emission lines. Using those two pixel positions of the emission lines and their known wavelengths, construct a linear wavelength calibration:

$$\lambda = c_0 + c_1x \tag{1}$$

You may face a challenge if the emission lines are contaminated by the stellar absorption lines. If so, find a way to work-around that contamination. Report your final wavelength calibration and estimate the uncertainty in the wavelengths at each pixel from that calibration. This uncertainty might come from your estimate of the pixel accuracy (and associated wavelength accuracy) of the positions of the sodium emission lines. Are those positions accurate to 1/10, 1/100, 1/1000 of a pixel or roughly what accuracy?

4 The Doppler Effect: Measuring the Observed Wavelength of Stellar Lines

Now you can measure the wavelength of two sodium D lines in your stellar spectrum. You can do this by the same technique you used to determine the pixel position of the sodium emission lines, starting with use of the cursor to get an approximate pixel position of the "core" of the center of both lines in absorption.

To then measure the pixel position of the absorption line to the nearest 1/1000 pixel, you may want to use a centroid routine (as before) or you may want to fit a parabola to the core of the line. If you use the centroid approach, you may want to turn the stellar spectrum upside down to make the absorption appear as emission lines. Also, if the emission line overlaps with the absorption line, you may need to interpolate the line, i.e., replace it by some simple functional (typically a first or second-order polynomial) or remove these pixels from your fit/centroid program. Make a table of the pixel position of each stellar line and each emission line (from the night sky), and the associated wavelength of each, based on the above wavelength calibration.

4.1 Measuring the Doppler Shift

The Doppler shift of each absorption line is the difference between the observed wavelength, λ_{obs} and the laboratory rest wavelength, λ_{rest} .

Again, you must use the rest (i.e., laboratory) wavelengths of each of your two sodium lines, and then take the difference, $\Delta\lambda$, between the observed and laboratory wavelengths for both absorption lines in the star's spectrum. Add to your table, listing the $\Delta\lambda$ for both sodium lines in the star.

Finally compute the Doppler shift of the star for each absorption line by using the Doppler formula:

$$v/c = \Delta\lambda/\lambda \quad (2)$$

Take the average of your two Doppler shift measurements to get the final Doppler shift of the star, i.e. its radial velocity in units of km/s. What is the uncertainty in your measurement of the radial velocity?

Wait! The Earth orbits the Sun, causing a Doppler effect simply due to the Earth's motion toward or away from the star. Apply the correction for the Earth's orbital motion relative to the Barycenter of the Solar System which is an inertial frame! You will have to contact Howard Isaacson (who helped you take the spectrum) to ask him the barycentric correction for your spectrum. The final result is the radial velocity of the star with respect to the barycenter of the Solar System. The star you observed will likely be monitored over the next few months/years to search for a signature of a planetary-mass companion. You have obtained the very first measurement in this series!