

# Lab: Measuring Doppler Shifts

## 1 Introduction

In this lab, we will measure the Doppler shift of the spectra of stars. Doppler shifts are used to measure the line-of-sight component of the velocities of nearly all astronomical objects, from planets, to stars, to nebulae, and galaxies. They can be used wherever spectral lines exist, including all parts of the electromagnetic spectrum.

## 2 The Spectra

Spectra were obtained at the Keck telescope using the “HIRES” spectrometer. At the back of the spectrometer is a CCD that detects the spectrum, with each pixel sensing the photons from a different wavelength. Each successive pixel contains the photons detected (counts) from a successive neighboring wavelength.

You will use the spectra listed in Table 1, which contains a log of four stars and a thorium lamp. The thorium lamp contains thorium atoms in a gas that is excited by a large voltage of  $\sim 1$  kV. During de-excitation, the atoms emit light which enters the entrance slit of the spectrometer. The resulting thorium spectrum has emission lines of known wavelength, providing a calibration of the wavelength at each pixel along the spectrum.

To prepare for this lab, open a new directory:

```
mkdir dopp
```

and then “cd” to that directory.

To read in the spectra, and some programs, copy all files from the following directory to your new directory:

```
cp /home/gmarcy/doppler_shift/* .
```

File	Star	RA	DEC	V_bary (km/s)	Vmag	sp
rk68.95.dat	HD49674	06:51:30.4	+40:52:05	26.3881	8.10	G0
rk68.82.dat	HIP21276	04:33:54.23	+64:37:59	15.7361	8.53	G0
rk68.107.dat	HIP42491	08:39:44.69	+05:46:14	29.1651	9.18	G5
rk68.34.dat	GJ26	00:38:58.0	+30 36 57	-4.9226	11.0	M2
rk68.113.dat	Thorium_lamp					

Table 1: Program spectra and stellar information.

Using IDL, read the spectrum with the command:

```
restore, 'rk68.95.dat'
```

The output spectrum will have the name, “sp6895”.

To get spectral order 19, use the command:

```
spec = sp6895(*,19)
```

which you can check with:

```
plot,spec
```

### 3 Wavelength Calibration

You need to determine the wavelength of each pixel along the spectrum, known as a “wavelength calibration”  $\lambda(x)$ . You will use the known wavelengths of the emission lines in the thorium spectrum. You will use spectral order 19 only, so first get the thorium spectrum in order 19:

```
restore, 'rk68.113.dat'
thorium = sp68113(*,19)
plot,thorium
```

Each thorium emission line has a known wavelength, and a reference thorium spectrum is at:

<http://www.noao.edu/kpno/specatlas/thar/thar.html>

In that website, enter the approximate wavelength range of spectral order 19: 4915 to 4985 Angstroms. Figure 1 shows a *printed* version the Thorium spectrum (postscript file) to give a clearer view of that spectrum to help read the wavelengths.

By examining that laboratory spectrum of thorium and the listed wavelengths of the thorium lines on that webpage, you should be able to identify the lines in your thorium spectrum.

This identification of thorium lines will not be easy. When you have identified 7–10 thorium lines in both the laboratory atlas and in your spectrum, you now know their wavelengths from the atlas. You should determine the pixel location of each of those lines in your spectrum. You can determine the pixel of each line by using the `cursor` command. For higher precision, fit each thorium line with a Gaussian using IDL's `gaussfit`. You only need three terms in the Gaussian, one of which is the x-position (pixel) of the center of the Gaussian.

You should make a table of the pixel location and wavelength of 7-10 thorium lines in your spectrum.

## 4 Fitting a Polynomial to your wavelengths

From your table of wavelengths and pixels for the thorium lines, make a plot of wavelength versus pixel. Check that the points fall along a monotonic curve. It should be nearly linear, with slight curvature. You now want to know the wavelength of *every* pixel, by establishing a calibration equation. A cubic polynomial is adequate:

$$\lambda = c_0 + c_1x + c_2x^2 + c_3x^3 \quad (1)$$

You can find the values of the 4 coefficients by using the IDL function, `poly_fit`.

```
coef = poly_fit(x,y,3,/double)
```

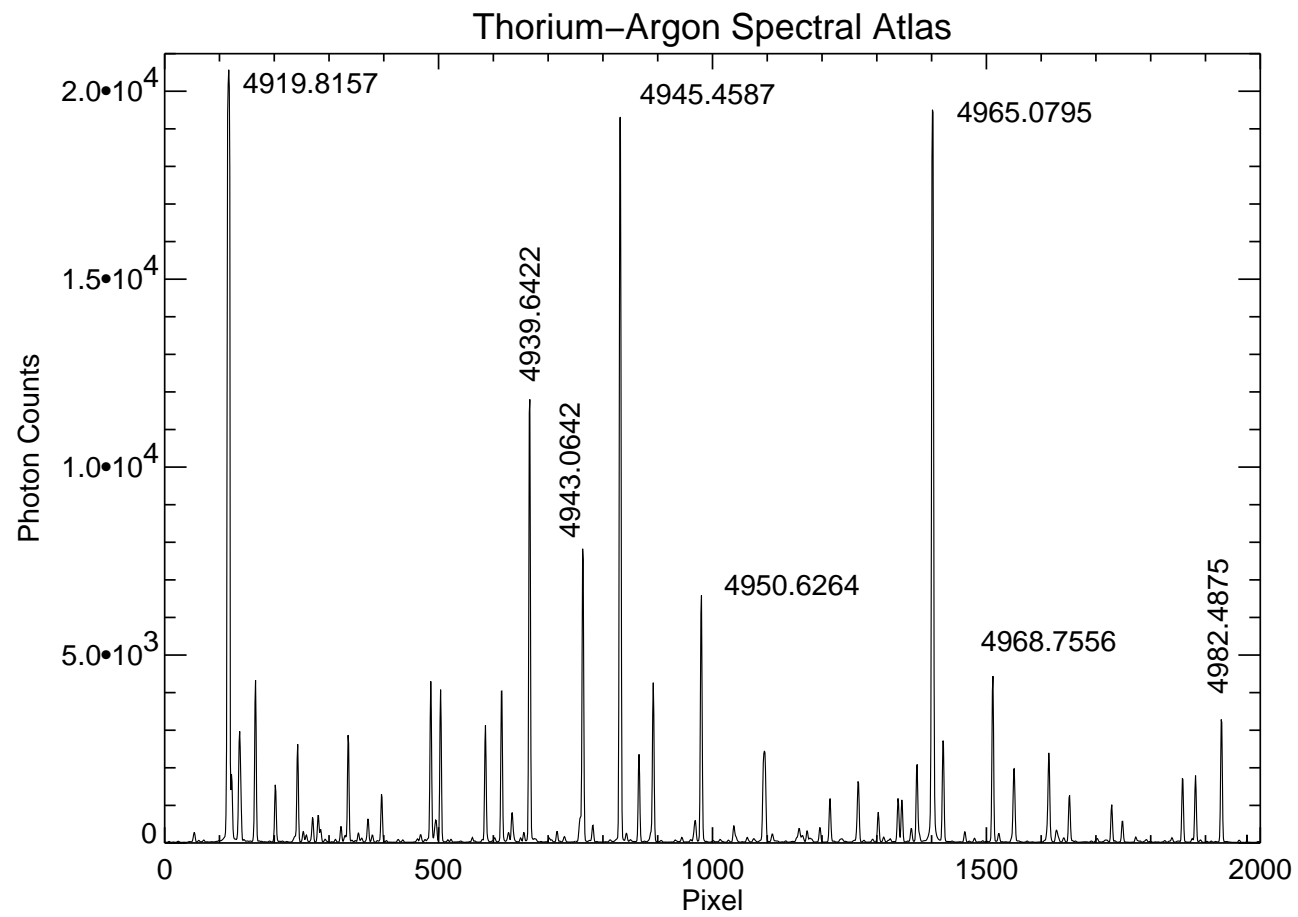


Figure 1: A portion of the Thorium-Argon spectrum, near order 19.

This `poly_fit` finds the coefficients for a cubic (hence the argument 3) and stores them in an array, `coef`. You should try a test case using values of `x` and `y` that nearly lie along a straight line and verify that the `poly_fit` produces coefficients that reproduces that straight line (or try a parabola).

The coefficients `coef` constitute a wavelength calibration. Equation 1 and `coef` give the relation between pixel location and wavelength at all points in the spectra. (The `double` keyword is required because of the large number (7) of significant digits of the wavelengths.)

## 4.1 Uncertainty in the wavelength calibration

Your wavelength calibration ( $c_0, c_1, c_2, c_3$ ) isn't perfect, and indeed it introduces errors into your Doppler shift measurement. Therefore, you must estimate the uncertainty in your wavelength calibration.

At any particular pixel, what is the uncertainty in the wavelength as determined by your calibration equation? One diagnostic of your errors stems from the discrepancies of the measured wavelengths of the thorium lines from the wavelength as computed by your calibration equation. The values of  $x_i$  and  $\lambda_i$  that you input into `poly_fit` do not sit exactly on the cubic polynomial.

For a given pixel  $x$ , the value of  $\lambda$  coming from your polynomial is slightly different from the *measured* value of  $\lambda$ . The difference between the measured and computed value of  $y$  in any least-squares fit is called the “residual” of the fit. The typical residual is your uncertainty. You should use the standard deviation of the residuals as the uncertainty in your wavelengths that are computed by your cubic polynomial.

Alternatively, you might measure the pixel position of one or two additional thorium lines of known wavelength. The difference between the known wavelength and the computed wavelength from your previously-determined polynomial gives an independent measure of the error in your wavelength from your calibration. In your final Doppler measurement, one source of error comes from this uncertainty in the wavelength calibration.

## 5 Measuring the Observed Wavelength of Stellar Lines

Now you can measure the wavelength of 5 lines in your stellar spectrum. You can do this by the same technique you used to determine the pixel position of the thorium lines: using the cursor and/or a Gaussian-fitting routine. If you use a Gaussian fit, the amplitude will be negative for your absorption lines. This is not a problem, as you only want the pixel position of the center of the Gaussian. (But, if you're uncomfortable, you may want to turn the stellar spectrum upside down on the computer to make the absorption appear as emission lines, or you can simply stand on your head.)

Make a table of the pixel position of each stellar line and the associated wavelength of each, based on the above wavelength calibration.

## 6 Measuring the Doppler Shift

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

The Solar Spectrum provides a good reference spectrum to identify absorption lines in cool stars. The Solar Spectrum in your wavelength region is given in Figure 2, and also at:

`solar_spectrum.ps`

Table 2 gives the rest wavelengths of some prominent absorption lines in that Solar Spectrum. These wavelengths are accurate to within 50 meters/sec in Doppler shift. These rest wavelengths can be used to determine the Doppler shift of all FGK-type stars.

You must find the rest wavelengths of each of your 5 stellar lines, either from the list in Table 2 or from the solar spectrum. Then take the difference,  $\Delta\lambda$  between the observed and laboratory wavelengths. Make a table (or augment the previous one) giving  $\Delta\lambda$  for each line.

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

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

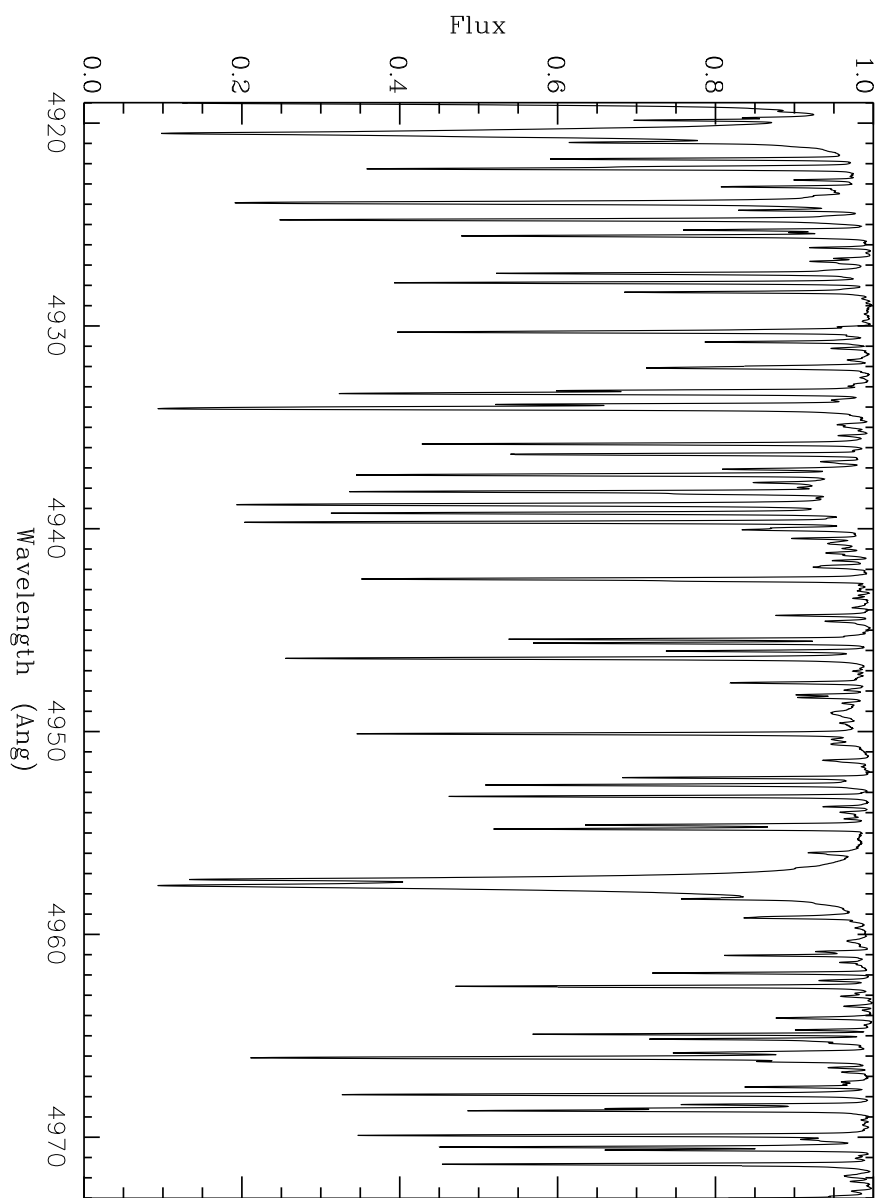


Figure 2: A portion of the solar spectrum, near order 19.

Line	LambdaF (Ang)	err (Ang)	Ion	Exc Pot. (eV)	log(gf)
2482	4923.9347	0.0018	FE2	2.89	-1.43
2483	4924.7770	0.0015	FE1	2.28	-1.99
2486	4925.5701	0.0014	NI1	3.65	-0.91
2490	4927.8732	0.0012	FE1	2.00	-3.22
2491	4928.3386	0.0016	TI1	2.15	-0.13
2493	4930.3155	0.0017	FE1	3.96	-1.35
2499	4934.0856	0.0015	FE1	4.15	-----
2504	4937.3520	0.0016	NI1	3.61	-0.40
2506	4938.1788	0.0012	FE1	3.94	-1.00
2507	4938.8221	0.0011	FE1	2.87	-1.02
2508	4939.2425	0.0020	FE1	4.22	-1.01
2510	4939.6941	0.0015	FE1	0.86	-3.17
2513	4942.4844	0.0019	CR1	0.94	-2.12
2534	4954.8081	0.0022	CR1	3.12	-0.35
2535	4957.3086	0.0014	FE1	2.85	-0.46
2537	4957.6076	0.0019	FE1	2.81	0.13
2540	4961.9193	0.0016	FE1	3.63	-2.46
2542	4962.5760	0.0014	FE1	4.18	-1.32
2559	4973.1065	0.0025	FE1	3.96	-0.74
2561	4975.3601	0.0060	TI1	2.50	-0.24
2563	4976.1372	0.0018	NI1	3.61	-1.40
2564	4976.3300	0.0017	NI1	1.68	-3.03
2566	4977.6518	0.0012	FE1	3.93	-2.16
2567	4978.1874	0.0018	TI1	1.97	-0.40
2568	4978.6026	0.0026	FE1	3.98	-0.94
2571	4980.1792	0.0022	NI1	3.61	0.05
2573	4981.7398	0.0016	TI1	0.85	0.52
2575	4982.5079	0.0017	FE1	4.10	-0.19
2576	4982.8216	0.0021	NA1	2.10	-1.02
2577	4983.2577	0.0015	FE1	4.15	-0.31
2578	4983.8609	0.0017	FE1	4.10	-0.24
2579	4984.1211	0.0017	NI1	3.80	0.10
2580	4985.2600	0.0019	FE1	3.93	-0.59
2581	4985.5546	0.0018	FE1	2.86	-1.38
2582	4985.9839	0.0022	FE1	4.26	-1.87

Table 2: Selected solar absorption lines. From “Accurate wavelengths in the Sun spectrum” (Allende Prieto & Garcia Lopez, 1998, A&A Supp, 131, 431)



Take the average of your five Doppler shift measurements to get the final Doppler shift. What is the uncertainty in your measurement of the Doppler shift?

Determine the Doppler shift for all four stars in Table 1.

Wait! The Earth orbits the Sun, causing a “false” Doppler effect. Apply the correction,  $V_{bary}$  (in Table 1), for the Earth’s orbital motion relative to the Barycenter of the Solar System which is an inertial frame! Use the barycentric corrections given in table 1 above which is defined to be positive for (earth) velocities toward the star. The final result is the radial velocity of the star with respect to the barycenter of the Solar System.