Radial Velocities of four Stars

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ABSTRACT

The radial velocities of four stars, HD49674, HIP21276, HIP42491, KH15D, were calculated relative to the Barycenter of our Solar System. This was accomplished with a wavelength calibration using a thorium-argon sample. A gaussian fit procedure was used to determine the center of the spectral lines on the CCD and convert them to wavelengths. Then the doppler shift equation was used to find the velocity.

The radial velocities of these stars can be found in Table. 8.

1. Introduction

Stellar spectra of the stars HD49674, HIP21276, HIP42491, KH15D were obtained from the Keck telescope. The wavelength calibration for the CCD was done with a thorium lamp over order 19, -from about 4915 to 4985 Angstroms. The spectra were analyzed in the following manner: The spectra of the stars were taken, and gaussian fits were used to find the indexes that correspond to the centers of the spectral lines. The wavelength calibration was used to convert these indices to a wavelength. The doppler shift was found using lines from the solar spectrum, and finally, a barycentric correction applied.

Star	RA	DEC	V_{bary} (km/s)	V_{mag}	SP
HD49674	06:51:30.4	+40:52:05	26.3881	8.10	GO
HIP21276	04:33:54.23	+64:37:59.4	15.7361	8.53	GO
HIP42491	08:39:44.69	+05:64:14.0	29.1651	9.18	G5
KH15D	06:41:10.18	+09:28:35.5	27.0290	15.	?

Table 1: Stellar Information

2. Data

To determine the wavelenghth of stellar spectral lines, first it was necessary to determine the wavelength that corresponds to each pixel on the CCD that recorded the data. To find this, spectra of a thorium-argon sample was compared with known wavelengths of ThAr emission lines. These known wavelengths, reported by Daryl Willmarth, Matt Cheselka, Mike Fitzpatrick and Matthew

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Rippa at NOAO,[2] were used to do wavelength calibration in a manner describe below. A gaussian procedure was used to determine the pixel location of several lines in the ThAr spectrum. The gaussian was fit over the emission lines of the gas, and the center of the gaussian was taken to be the pixel location of the emission line. The wavelength of every pixel was found by fitting a fifth-order polynomial to our pixel values and their wavelengths from NOAO. A fifth-order polynomial with coefficients represented by $C_{\#}$:

$$\lambda = C_0 + C_1 x + C_2 x^2 + C_3 x^3 + C_4 x^4 + C_5 x^5 \tag{1}$$

The polynomial (Equation.1) gives a straight line, shown in Figure. 1. This means that the wavelength increases linearly along the index of the CCD. A cubic polynomial was fit at first, but more accuracy was desired -hence the fifth-order polynomial. It is apparent in Table .1 how much more accurate the fifth-order polynomial is. All the wavelengths are accurate to 0.001 Angstroms, and many are more accurate than that; the average error is 0.00034 Angstroms.

Pixel Values	ThAr Line	From New Coefficients	From Old Coefficients
195.7859	4921.6134	4921.6133	4921.48
365.3357	4927.7803	4927.7802	4927.69
516.0661	4933.2091	4933.2091	4933.13
615.8228	4936.7746	4936.7739	4936.70
645.4885	4937.8295	4937.8297	4937.76
696.5669	4939.6422	4939.6427	4939.57
861.5513	4945.4587	4945.4582	4945.39
1432.1850	4965.0795	4965.0805	4965.15
1451.4920	4965.7315	4965.7306	4965.81
1959.41731	4982.4875	4982.4873	4983.16

Table 2: Calculated Thorium pixel values, wavelengths, and wavelengths given by the coefficients from a fifth-order polynomial(Column 3) and by a cubic polynomial (Column 4) for these same wavelengths. All wavelangths and in Angstroms

The solar spectra was analyzed using a gaussian fit procedure as well. This was done because it would provide more options when analyzing the stellar spectra; some of the wavelengths for absorption lines were provided, but if the wavelengths for more solar lines were known, then more stellar lines could be analyzed. Also, running the gaussian fit procedure over the solar spectra and comparing the data given by the procedure to known values gives an idea of the accuracy of the procedure. In this case, the procedure gave the same wavelength (in Angstroms) to an accuracy of the second decimal place. The error in the solar spectrum corresponds to 50 m/s.

[2] email:http://www.noao.edu/kpno/specatlas/thar/thar.html

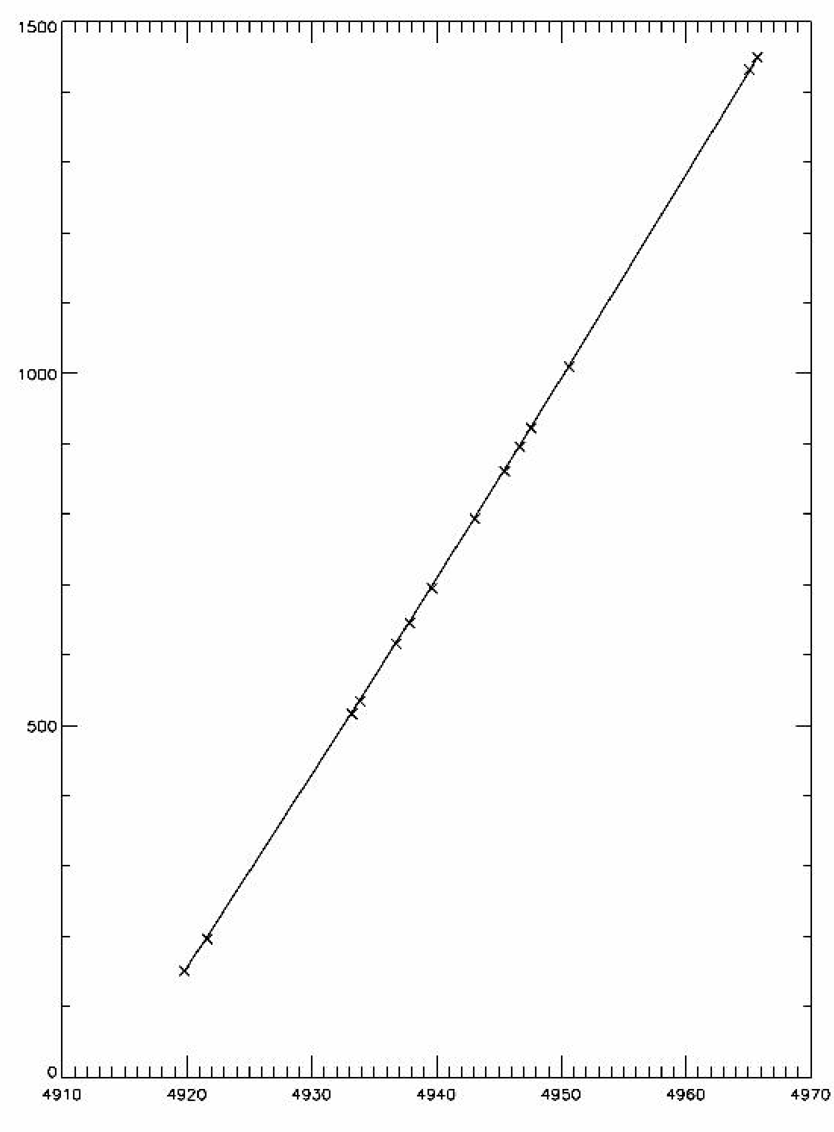

Fig. 1.— The fitted polynomial correlating pixel values to wavelengths.

Coefficients
C_0 = 4914.4150
C_1 = 0.036972006
C_2 = -1.0325557e-06
C_3 = -1.0143220e-10
C_4 = 4.9759025e-14
C_5 = -1.3065483e-17

Table 3: The coefficients for the fifth-order polynomial.

The stellar spectra of the four stars were then analyzed using the gaussian fit procedure. Due to the nature of the lines, and the program, not all of the lines would give good index values. 7 to 10 lines were analyzed per spectrum. The first three stars are G-type stars, so the solar spectrum can be used to calculate the doppler shift. The spectral type of KH15D is unknown, but in this lab, the stellar spectra was used to moderate success. A plot of the stellar spectra against the sprectra of KH15D shows that it is close enough for analysis, but few lines could be analyzed. This spectrum was problematic. There were erroneous pixel values created by broken pixels in the CCD. These were replaced with the average value of the spectrum and avoided during analysis. If I had been cross-correlating the stellar spectrum with the solar spectrum, I would have needed to generate random noise that had an average value that was the same as the spectra and replaced the bad pixel values with that. This would have been necessary for a cross-correlation so that I did not accidentally create a flat space that matched up with an area in the solar spectrum, resulting in a 'mis-alignment' of the spectra. Because I did not end up using cross-correlation, this was not necessary. For this particular spectrum, a gaussian fit, a polnomial and a wieghted polynomial were tried over all the lines that looked like they were doppler shifted spectral lines. Attempts over three lines wer successful. Four more lines were examined by eye, basically by zooming in on the peak until it could be estimated, to a decimal place, where the center of the line was.

The doppler shift was found by subtracting the wavelengths for the corresponding spectral lines in the solar spectrum. The velocity of the star was found using the doppler equation:

$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda_{rest}} \quad (2)$$

The uncertainty is reported using poisson statistics in all of the tables in this paper.

Solar $\lambda(\AA)$	Pixel Value	$\lambda(\AA)$	$\Delta\lambda(\AA)$	V_{rad} (km/s)
4927.4225	349.25857	4927.1982	-0.22419765	12.747
4927.8737	361.34840	4927.6359	-0.23762367	11.931
4930.3155	428.42804	4930.0588	-0.25662339	10.783
4938.8195	666.54810	4938.5779	-0.24142418	11.733
4939.2425	678.41552	4938.9991	-0.24355548	11.605
4939.6912	691.08820	4939.4486	-0.24285260	11.649
4942.4828	770.57086	4942.2590	-0.22390912	12.806
4950.1118	987.85428	4949.8676	-0.24419660	11.598
4953.2132	1077.27932	4952.9671	-0.24628981	11.481
4962.5760	1350.96496	4962.3352	-0.24097868	11.830
Mean V_{rad} (km/s)	σ	σ_{mean}		
11.8168	0.593123	0.187562		

Table 4: Data for HD4967: $\Delta\lambda$ is calculated by subtracting the third column form the first, and the velocity is given with respect to the center of our solar system.

Solar $\lambda(\AA)$	Pixel Value	$\lambda(\AA)$	$\Delta\lambda(\AA)$	V_{rad} (km/s)
4927.4225	351.73539	4927.2879	-0.13449170	7.553
4927.8737	363.91958	4927.7290	-0.14456936	6.940
4930.3155	431.12722	4930.1561	-0.15933971	6.047
4938.8195	669.15443	4938.6704	-0.14889086	6.698
4939.2425	681.08190	4939.0937	-0.14896235	6.694
4939.6912	693.74707	4939.5428	-0.14860279	6.717
4942.4828	773.16185	4942.3504	-0.13253721	7.696
4950.1118	990.51682	4949.9602	-0.15164264	6.552
4953.2132	1080.04081	4953.0625	-0.15087613	6.604
4962.5760	1353.75309	4962.4297	-0.14647240	6.887
Mean V_{rad} (km/s)	σ	σ_{mean}		
6.83921	0.480588	0.151975		

Table 5: Data for HIP21276: $\Delta\lambda$ is calculated by subtracting the third column form the first, and the velocity is given with respect to the center of our solar system.

Solar $\lambda(\AA)$	Pixel Value	$\lambda(\AA)$	$\Delta\lambda(\AA)$	V_{rad} (km/s)
4927.4225	333.40578	4926.6237	-0.79868174	-19.428
4927.8737	345.51640	4927.0626	-0.81093133	-20.168
4930.3155	412.70471	4929.4918	-0.82364474	-20.917
4938.8195	650.37553	4938.0034	-0.81595087	-20.364
4939.2425	612.24847	4938.4252	-0.81744902	-20.450
4939.6912	674.92793	4938.8754	-0.81603766	-20.367
4942.4828	754.23201	4941.6825	-0.80045573	-19.387
4950.1118	971.27735	4949.2910	-0.82081040	-20.545
4953.2132	1060.59128	4952.3901	-0.82327114	-20.663
4962.5760	1333.92861	4961.7573	-0.81886392	-20.303
Mean V_{rad} (km/s)	σ	σ_{mean}		
-20.2597	0.494264	0.156300		

Table 6: Data for HIP42491: $\Delta\lambda$ is calculated by subtracting the third column form the first, and the velocity is given with respect to the center of our solar system.

Solar $\lambda(\AA)$	Pixel Value	$\lambda(\AA)$	$\Delta\lambda(\AA)$	V_{rad} (km/s)
4927.8737	368.013	4927.8771	-0.013547056	27.244788
4937.3499	631.5	4937.3321	-0.018017203	25.935007
4938.8195	672.75	4938.7981	-0.021261018	25.738429
4939.2425	684.973	4939.2317	-0.010949539	26.364406
4950.1118	993.6	4950.0673	-0.044488901	24.334628
4957.3086	1202.3	4957.2687	-0.039892486	24.616507
Mean V_{rad} (km/s)	σ	σ_{mean}		
25.7056	1.08835	0.344166		

Table 7: Data for KH15D:$\Delta\lambda$ is calculated by subtracting the third column form the first, and the velocity is given with respect to the center of our solar system.

Radial Velocities
HD49674 11.817 $\pm$ 0.189
HIP21276 6.839 $\pm$ 0.152
HIP42491 -20.260 $\pm$ 0.156
KH15D 25.706 $\pm$ 0.344

Table 8:

3. Interpretatons

The radial velocities for the four stars are found in Table. 8. These results are very pleasing, and the best that can be hoped for with this method. For higher accuracy, a cross-correlation of the solar spectra with the stellar spectra should be done.

The analysis of the thorium-argon sample ended up being the area of this project where the most care was necessary. A polynomial was used to determine the wavelength calibration. The coefficients of this polynomial were created by correllating the pixel values of the thorium-argon spectral lines to their known laboratory values. If these coefficients were even slightly off, it resulted in the introduction of a huge error to the radial velocity.

Error in the coefficients could be introduced by mismatching a line value to what looks like a single spectral line, but which is actually a double line. The sample of ThAr used by the NOAO research group produced lines with slightly different intensities than the sample from the Keck telescope. If, during the analysis to find the center of the ThAr spectral lines, a double line was chosen that looked like a single line, and the intensity of the two peaks had shifted, then the center of one line could be matched with the wavelength of the other. This would throw the coefficients slightly off, -but off enough to change the final velocity determined for the star. I believe this is what happened with the first set of coefficients that were used to determine wavelengths and finally, the velocities of stars.

Error was also introduced by a poor gaussian fit. This was not so much the case for the thorium lines, which gave very good fits. The gaussian procedure used over the spectral lines of the four stars returned plot of the spectral line with the gaussian fit plotted over it, as well as the doppler shift and the barycentric velocity. This made it easy to visually check the gaussian fit, and see that even a slightly poor fit gave a velocity that had a greater standard deviation from the mean than the rest of the data set. There were a few lines that were poor fits for three of the stars. One of these lines was such a poor fit that it was thrown out. The rest were kept. During initial analysis, the procedure that was run did not plot out the spectral line, and it's gaussian. Instead, the line thickness returned by the gaussfit procedure was used to check the fit and make sure it was not a double line. After performing the analysis again, I believe that this information is good to have, but is not good enough to give the kind of accurate results desired.

The uncertainty is calculated using poisson statistics in all of the tables in this paper. The errors in the radial velocities, see Table. 8, seemed very low. So, in order to gauge the accuracy of these errors, I went back to the wavelength calibration. The average residual was .00034 Angstroms. This was divided by the average wavelength and multiplied by the speed of light to get an approximate error in km/s. The error was 0.02 km/s, which is smaller than the error in the solar spectrum, which is 0.05 km/s. It appears that the error was introduced through the use of a gaussian.