Creating a Pipeline to Generate Radial Velocity Curves from Raw APF Spectral Data

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Abstract

The goal of our project is to find binary star systems by analyzing stellar spectra to measure radial velocities. We collected data from the APF at Lick Observatory from 28 young stars. Gathering the stellar spectra of these star systems allows us to plot their radial velocity curves. If a binary companion exists, we can characterize them by using the radial velocity measurements to calculate constraints on the companion's mass and orbital period.

Background

Binary star systems are systems of two stars moving together with a gravitational force around a common center of mass. Spectroscopic binaries are systems that from Earth appear as a singular star, however, spectral features of the stars reveal shifts which we can analyze to confirm a gravitational pair. These spectral shifts are called Doppler Shifts, and the basis of our project is taking our spectra and finding doppler shifts. The Radial velocity method is a method we use by determining if spectra are red shifted or blue shifted. We can look at the star's spectrum at a moment in time, then look at another moment in time and calculate the velocity of the star overtime between the separate observations [1].

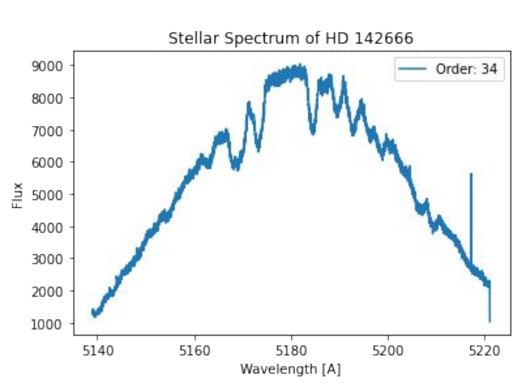
Doppler Shift Equation:

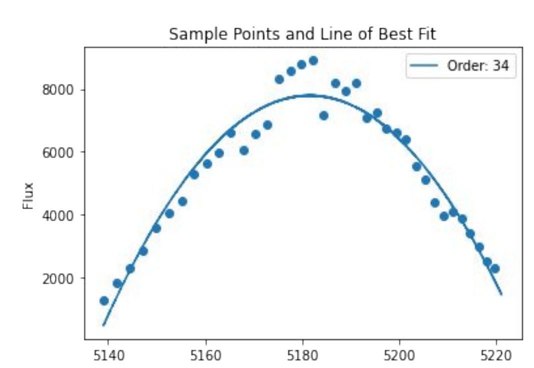
$$\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$$

Our data is from the Automated Planet Finder (APF), at Lick observatory in San Jose, CA. We've been permitted to use an unpublished dataset belonging to the Czekala Group at Penn State consisting of observations of 28 known singular stars over periods of time. When using the radial velocity method (or Doppler spectroscopy), we can look at single star systems to determine if it is actually a binary system.

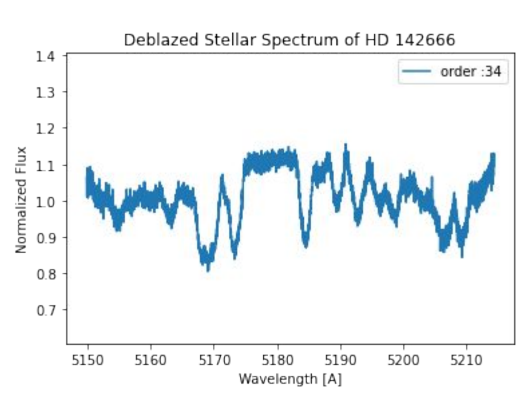
Methodology

We did our work in Python where we took in inputs of raw APF stellar spectra to generate radial velocity time series for a given star. To begin, we read in the stellar spectra and began to clean the data of artifacts present as a consequence of the telescope's optics. This consisted of deblazing, normalizing, and cropping the data. Deblazing is a process that is necessary to correct stellar data of an artificial curve due to the echelle grating, which aids in focusing the telescope optics over different regions of the electromagnetic spectrum.





We deblazed our spectra by matching an evenly-spaced sample of our data to a quadratic function, and dividing the found function from each data point. This resulted in a spectrum without artificial noise due to the echelle grating. We can deblazing gets rid of the artificial curve but maintains the spectral features.



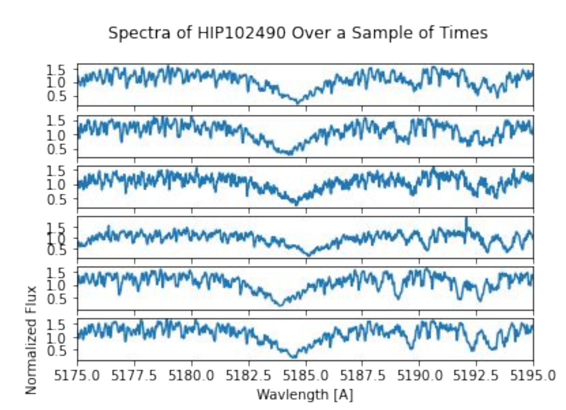
Methodology Cont.

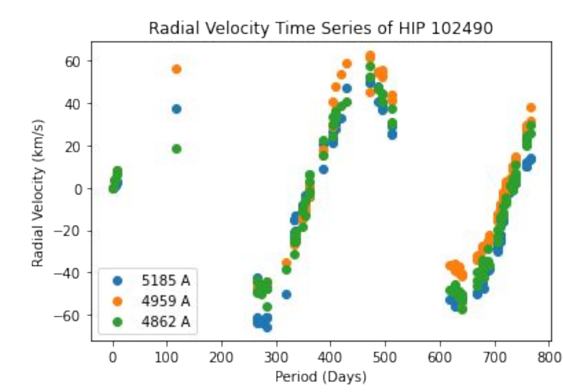
Our next step was to calculate changes in radial velocity over a period of time. The Doppler effect causes changes in the observed wavelength of light due to changes in the velocity of an object. Calculating changes in observed wavelength allows us to convert our doppler shift measurements to velocity measurements. We created a python function to perform this task. Our code finds the wavelength value of the lowest flux point in a given wavelength region, with the goal of finding the observed wavelength of light in which an absorption feature appears.Using this function for finding wavelengths associated with absorption features, we can analyze the wavelength values of a given feature over multiple observations throughout a period of time. The time period over which we are able to generate radial velocity time series is constrained by the observations of a given star present in the dataset.

Though we are able to calculate velocities from doppler shifts, the deblazed data is still inaccurate as it includes Doppler shifts caused by Earth's radial velocity as it orbits around the sun. Correcting for Earth-caused doppler shifts, or performing a barycentric correction, we are able to ensure the doppler shifts calculated are solely representative of the star's motion.

Knowing the velocity of the Earth at a given point, we are able to subtract out the Doppler effect. Finding the change in wavelength associated with the velocity is simply calculated using the doppler shift formula; once we have this value for a given instance in time, we are able to correct this by subtracting the change in wavelength from the observed wavelength generated using our previous function.

Collecting the wavelength data of absorption features over time for multiple different features gives us a sense of our accuracy for the star's radial velocity. We generated a radial velocity time series that matches a binary characterized in 2005 [2].

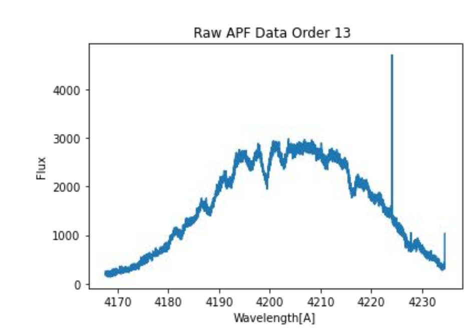


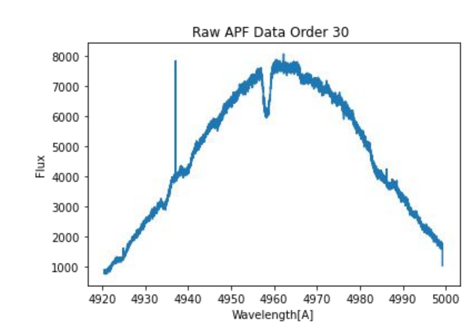


Analysis

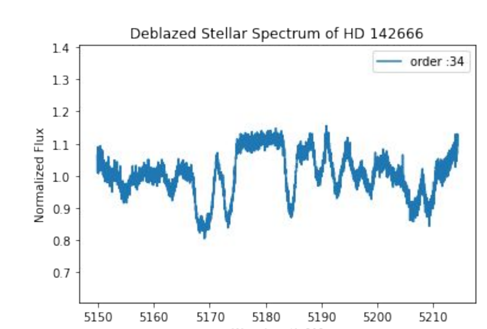
Orders taken from the original, raw data from the Automated Planet Finder. Orders are a portion of the entire spectrum. If you stitch together all the orders, you would get the complete spectrum of the star. The graph represents how much light the star is emitting. The lower orders correspond with how much light in the low wavelength region the star is emitting whereas the higher orders are showing how much light in higher wavelength regions the star is giving off. If we look at the successive observations, we can see how it is moving back and forth. This suggests that there may be a binary companion.

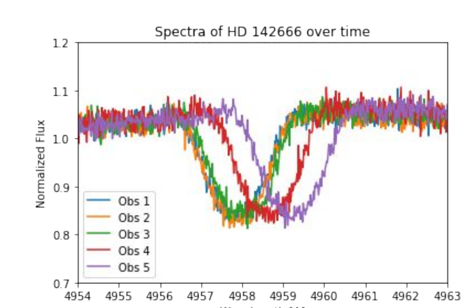
Raw stellar spectra:





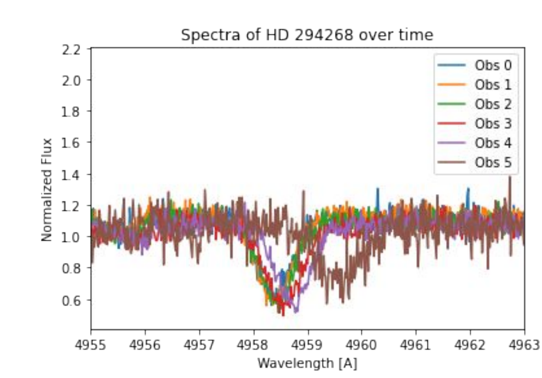
Deblazed Data:

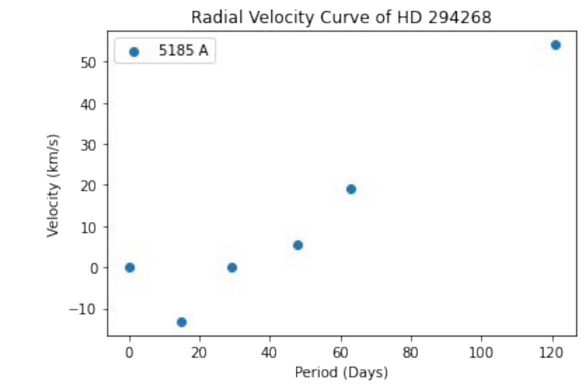




Since we know our code generates accurate radial velocity curves, we generated some using our data. Both figures are taken from the same data of the star HD 294268.

Analysis Cont.

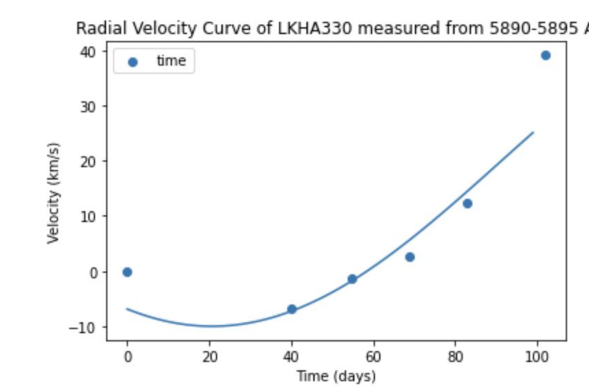


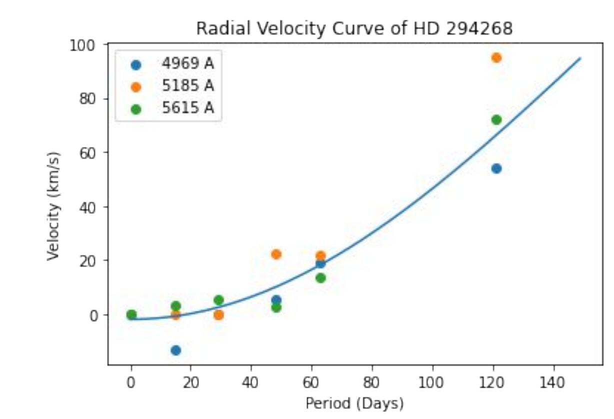


These graphs on were made by focusing on the absorption feature between 4954 and 4962 Å. This radial velocity time series seems to show a sinusoidal trend, inferring that the star may have a companion. If the time series showed a horizontal line, it would suggest that there is no movement, and thus no binary companion. Through the collection of more data, we can make a more detailed and complete curve of the star's radial velocity, otherwise we may try to match artificial curves to the data..

Results

Looking at the radial velocity curve, we can determine whether the given star has a radial velocity change over time that would fit a sinusoidal curve. This shows the star may have a companion that provides a gravitational pull, causing the primary star to fluctuate periodically. Below are examples of the radial velocity curves we generated for LKHA 330 and HIP102490. We fit curves to the graphs, which means the stars we analyzed could potentially be in a binary system.





Conclusion and Future Work

As the search for spectroscopic binary systems continues, it is important to understand how these systems provide insight into how the universe works. Binary stars are of immense importance to astronomers as they allow the masses of stars to be determined by analyzing orbits. Through this research, we created a radial velocity pipeline that generates radial velocity curves to detect spectroscopic binary systems. Using the conclusions from our research project, we can detect spectroscopic binaries using the generated radial velocity time series. Since the young stars we focused on have protoplanetary disks, our research also could be continued to give insight on the phenomenon of planetary formation. Gravitational interplay between two stars can eject matter to form a protoplanetary disc in which planets can form therefore, scientist use a similar method when searching for exoplanets [3].

References

1. Murray, C. D., & Correia, A. C. M. (2011, February 25). *Keplerian orbits and dynamics of exoplanets*. arXiv.org. Retrieved April 27, 2022, from https://arxiv.org/abs/1009.1738
2. Griffin, R. F. (2005). Spectroscopic binary orbits from photoelectric radial velocities - Paper 183: HD 98031, HD 112573, and HD 19791. *The Observatory*, *125*
3. Kounkel, M., Covey, K., Moe, M., Kratter, K. M., Suárez, G., Stassun, K. G., Román-Zúñiga, C., Hernandez, J., Kim, J. S., Ramírez, K. P., Roman-Lopes, A., Stringfellow, G. S., Jaehnig, K. O., Borissova, J., Tofflemire, B., Krolikowski, D., Rizzuto, A., Kraus, A., Badenes, C., ... Oravetz, A. (2019, March 27). *Close companions around young stars*. arXiv.org. Retrieved April 27, 2022, from https://arxiv.org/abs/1903.10523