Development of a T Tauri star spectral analysis infrastructure

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Abstract

The question of how planets form is one of the most fundamental of astronomy. Young star systems, especially T Tauri systems, offer a crucial view of the early formation of planetary systems. Circumstellar disks, which provide the raw material for planet formation, frequently form along with T Tauri stars and have been observed to accrete onto the central star. Both the stellar properties of T Tauri stars and the kinematics of circumstellar disk accretion can be analyzed by studying the high-resolution spectra of these young star systems. Absorption lines in the spectra mostly indicate properties about the star, while emission lines mostly indicate accretion properties of the star system. A software infrastructure to help automate the analysis of HIRES spectroscopy data of T Tauri systems recorded using the Keck Telescope. When complete, the notebook will enable users to determine stellar properties such as radial velocity, element abundances, spectral type, and rotational velocity, and accretion properties such as emission line equivalent widths, velocity profiles, and continuum veiling.

Introduction

Young star systems have been a subject of fascination for astronomy research, as these systems reveal a critically important and relatively short-lived period of the lifetime of a star system. Ever since the first discovery of exoplanets in 1992 (Wolszczan & Frail, 1992), and as over 1000 more have been discovered in recent years (Chou & Johnson, 2016), even more attention has been given to this topic. Young stars systems are intricate and dynamic, as their development is influenced by a variety of factors. A young star undergoes a variety of changes relatively quickly on the scale of millions of years, starting as a molecular cloud, then collapsing due to its self-gravity into a protostar where the star begins to heat up due to the gravitational collapse of the massive gas cloud. The star then becomes a T Tauri star, where the star becomes highly active, emitting jets of radiation at the poles, and where a well-defined circumstellar disk begins to form surrounding the star. After a star evolves through the T Tauri stage, it continues to contract in radius until it stabilizes as a main sequence star, in which it spends most of its life. Well-defined planets can form with the circumstellar disk eventually gone, depleted by the possible formation of planets, blown away by stellar radiation, and accreted onto the star.

One important process that T Tauri stars undergo is the gradual accretion of the circumstellar disk onto the star. Accretion rates have been measured to be relatively slow, with accretion rates of around 10-8 solar masses per year on average (Hartmann et al. 2016). While this rate may seem to be negligible, the timescales on which this stellar accretion occur last for millions of years, such that the star can accumulate approximately 10% of its mass over the duration of accretion.

Circumstellar disk accretion is theorized to be caused not only by gravitational attraction between the star and the disk, but also by magnetodynamic interactions between the ionized disk material and the star's magnetic fields. While the mechanisms that govern stellar accretion are complex, some recent developments have been made with understanding the nonideal magnetodynamic interactions that influence stellar accretion. Magnetohydrodynamic (MHD) simulations performed in recent years have shown how the process of accretion occurs with stars with varying dipolar fields (Bouvier et al. 2007, McGinnis et al. 2015), and how well-ordered accretion occurs with respect to stellar dipole field lines (Bouvier et al. 2007, Kurosawa & Romanova 2013).

Evidence for accretion can be seen in stellar spectra as the "filling in" or veiling of absorption spectral lines and in emission lines such as H-alpha, H-beta, He I, and Ca II. Thus, T Tauri stars offer a view into one of the most critical periods in star system's life, and direct observations allow for the study of young stars and currently forming planetary systems. Previous studies similar to those of Dr. Hillenbrand have determined stellar properties such as effective temperature, surface gravity, and veiling to verify whether young stellar object candidates belonging to specific star forming regions such as Lupus (Frasca, Biazzo, Alcalá, et al., 2017) and determining the effective temperatures of solar type stars by measuring the equivalent width ratios of temperature-dependent spectral lines (S. G. Sousa, A. Alapini, G. Israelian, and N. C. Santos, 2009). Since the formation of planets is highly dependent on the development of the circumstellar disk, further investigation of the way in which circumstellar disks accrete onto T Tauri stars must first be understood. Ultimately, the goal of this work is too apply the software to a set of Keck/HIRES spectra in the Upper Scorpius region of recent star formation, with a variety of objects ranging from young disk systems to old disk systems, as well as stars with no present disk material and have already formed planets.

Methods

Separate directories containing stellar spectrum files of the standard stars, young template stars, and object stars were created to organize the data used in the development and analysis of T Tauri systems. An additional directory was made to store the files containing the spectral lines and wavelength bands to import as resources for the software infrastructure.

To develop the software infrastructure for the analysis of the stars, an IPython Notebook running Python 2.7.12 was created for the development of the analysis tools to study the stellar and accretion properties of T Tauri systems. Development began with the implementation of previously-made code snippets for producing the velocity spectrum of a star relative to a given spectral line and code for reading in a spectrum file. For stellar analysis, modules were developed to read in, work with, display, and study spectrum properties as given. A module was developed to read in and return user-given wavelength ranges of stellar spectra within a CCD-order section, an entire section, or the entire spectrum file. To plot spectra, a variety of functions were created to display the spectra of multiple stars in one figure, residuals of normalized CCD flux values between a plot of two stars, and given spectral lines and wavelength bands (e.g. atmospheric bands, molecular absorption regions). Additionally, a module to estimate the signal-to-noise ratio of a spectrum file was developed using the CCD gain of the spectrum and the median flux of a region of continuum. Along with the use of atmospheric absorption bands, another module was created to return all the wavelength regions of emission lines and strong atmospheric absorption bands that could be excluded in uses such as spectra residual calculations.

Several modules were made to compare the spectra of two stars against each other by computing the chi-squared and root mean square errors between the two normalized spectra, which were then used to create another function that determines the most similar standard star to any other given star based on these star comparison modules. One important property of T Tauri stars to determine was stellar radial velocity, which can be used to help confirm whether a star is a member of a young cluster or whether a source is a binary system or a single star. To determine the radial velocity of a star, the radial velocity could be obtained from a list of known radial velocities if the star was a standard star, the measurement of the wavelength shift of a spectral line from the zero radial velocity value could be made, or the radial velocity could be obtained using a cross-correlation of one star relative to another star.

The measurement equivalent widths of absorption and emission spectral lines was implemented by creating modules that modelled spectral emission and absorption lines as Gaussian distributions. Using the equivalent width measurement module, a program that plots the ratios of two arbitrary pairs of spectral line equivalent width ratios was made. This program can identify the presence of certain spectral lines and the relative strengths of certain lines, which indicate the kinds of properties of the star in which the spectral lines formed such as temperature and surface gravity. For example, stars determined to have relatively low temperatures and low surface gravity can be confirmed as pre-main sequence members of a cluster. Further progress was made to determine the existence of specific emission or absorption lines in a star, and whether those lines are those of emission or absorption.

Additional plotting programs were created for analyzing the properties of M-type stars, which differ from the earlier spectral types due to the high abundance of both molecular absorption bands and gaussian-like atomic bands in M-type stars as opposed to earlier spectral types which contain few to no molecular absorption bands. One plotting function was created to plot the TiO wavelength band flux to continuum flux ratios (temperature-sensitive) versus CaH wavelength band flux to continuum flux ratios (surface-gravity-sensitive), which indicates the relationship between the temperature and surface gravity of M-type stars. Another type of program that plots the TiO wavelength band flux to continuum flux ratios versus the respective spectral type of stars was made with the help of a module that that converts spectral types into corresponding numerical values. This program was then used to develop another function that is able to determine the specific spectral type (e.g. M0, M1, etc.) of an M-type star based on the star's TiO wavelength band ratio to the continuum and the linear relationship between the TiO wavelength band ratio and spectral type.

For the analysis of the accretion properties of T Tauri star systems, additional modules were developed that specialized in applying mathematical operations to stellar spectra, making copies of original spectrum regions and modifying them to assess different accretion-related properties. To measure the veiling of a star, a module was created that incrementally added continuum flux to a template spectrum similar in spectral type to the object star being studied, returning the amount of continuum added that corresponded with the minimum chi-squared or root mean square error from the object star.

To determine the projected rotational velocity vsini of a given object star, a module was developed to convolve a Gaussian kernel with a given standard deviation with a given spectrum. This module was then used in the creation of a module that, similar to the veiling module, that convolved a template star spectrum with a Gaussian kernel with increasing standard deviation values, returning the standard deviation value corresponding to the minimum chi-square or root mean square error between the template and object spectra.

The last major module created for this software infrastructure was a velocity spectrum program that converts the wavelength values of a region of spectrum to doppler shift velocities relative to a spectral line, displaying the kinematics of matter accreting onto the central star.

Results

Below are test results for the most fundamental modules of the software infrastructure.

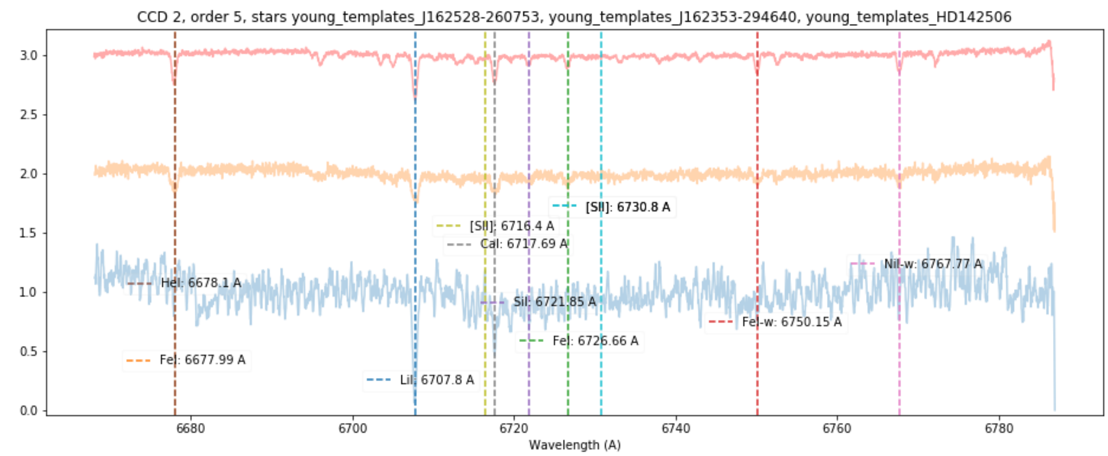

Fig 1. Spectrum plot of order 5 of CCD 2 of three stars including spectral lines marked with dashed lines.

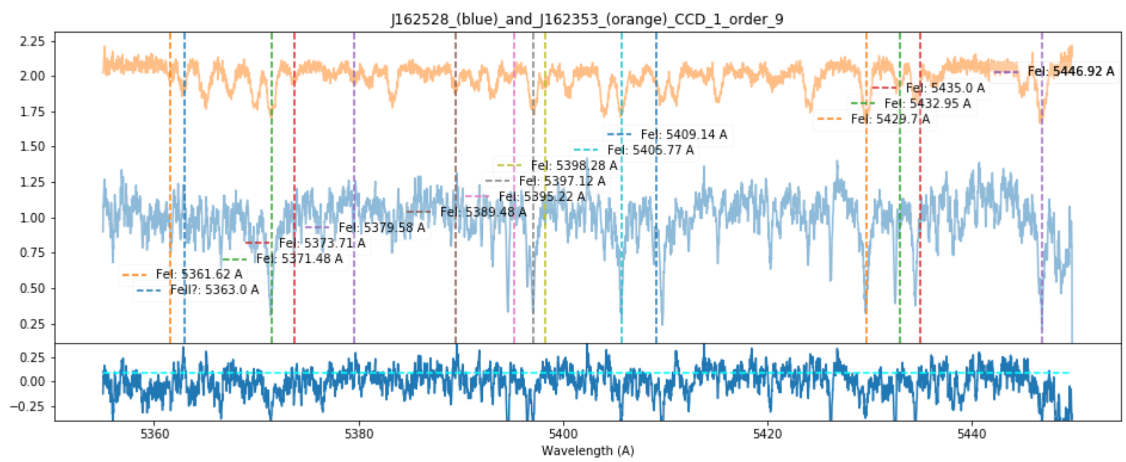

Fig 2. Plot of two stars with residuals below spectra for one order with spectral lines labelled. The cyan dashed line in the residual plot represents the square root median error between the two spectra.

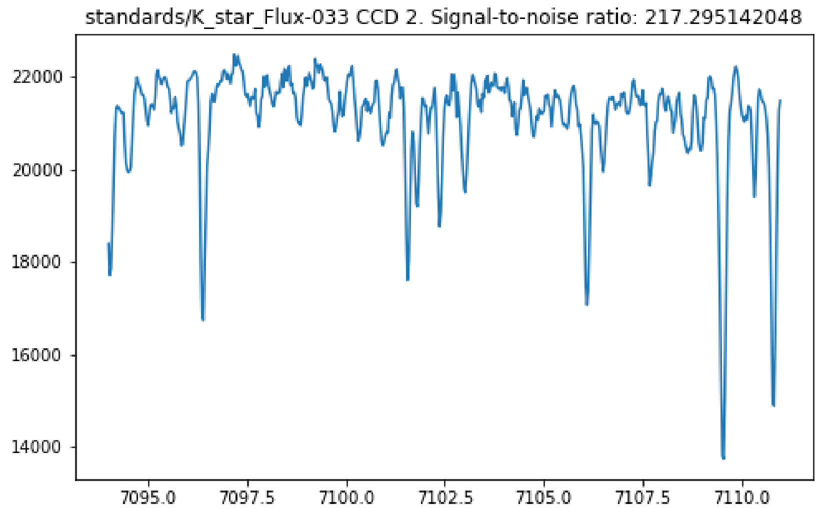

Fig 3. Signal-to-noise ratio of a star spectrum sampled over the plotted spectrum.

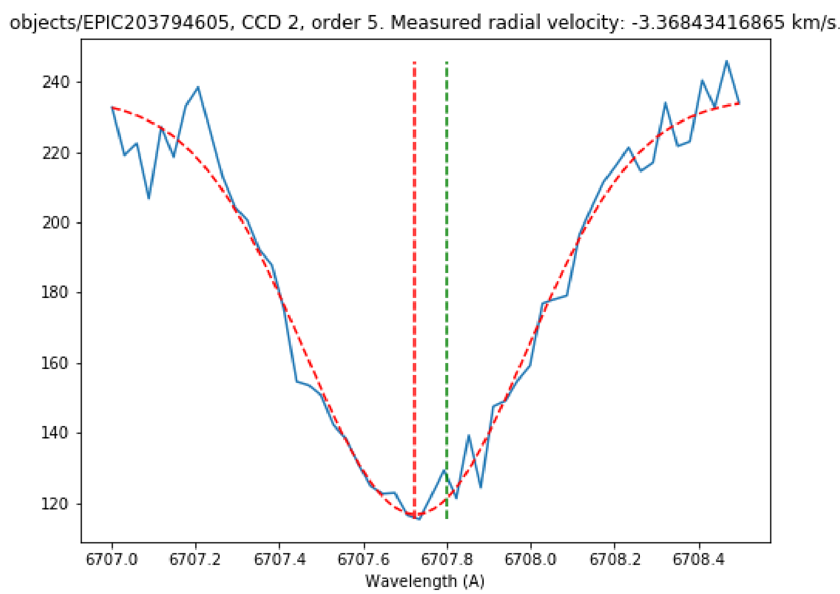

Fig 4. Radial velocity calculation based on the wavelength shift of the star's Li 6707.7 Å absorption line from the line's original position at zero velocity.

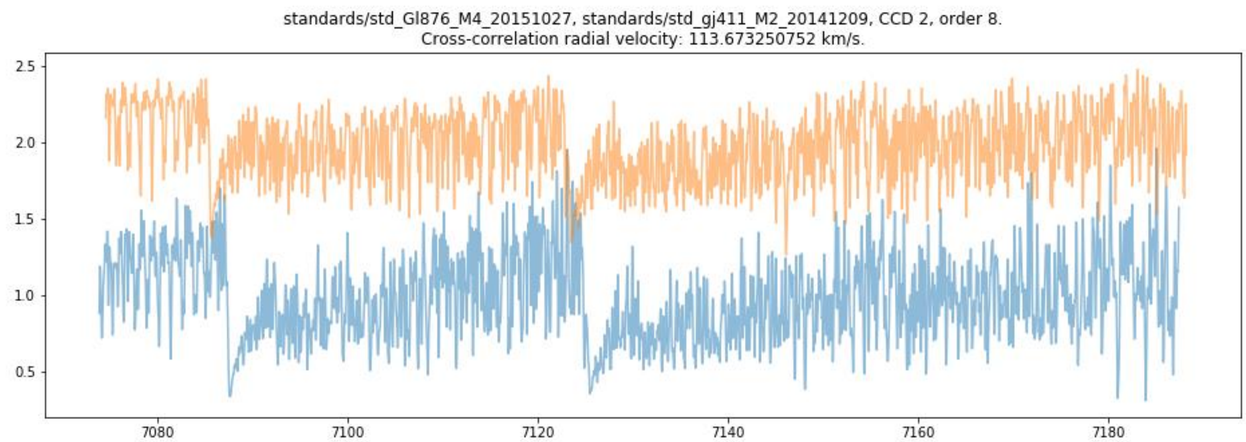

Fig 5. Radial velocity of the star std_Gl876_M4_20151027 with respect to the star std_Gj411_M2_20141209 calculated from the cross-correlation of the two spectra shown above.

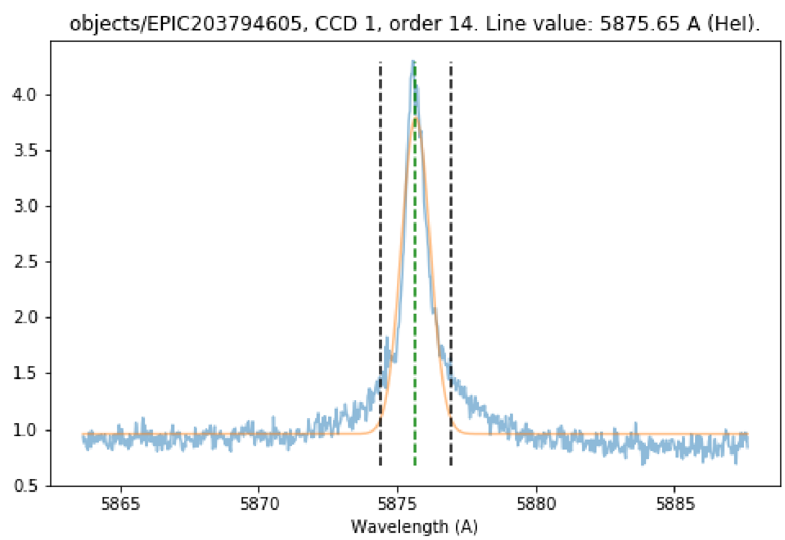

Fig 6. Plot of a star's emission line detection of the HeI spectral line located at 5875.65 Å.

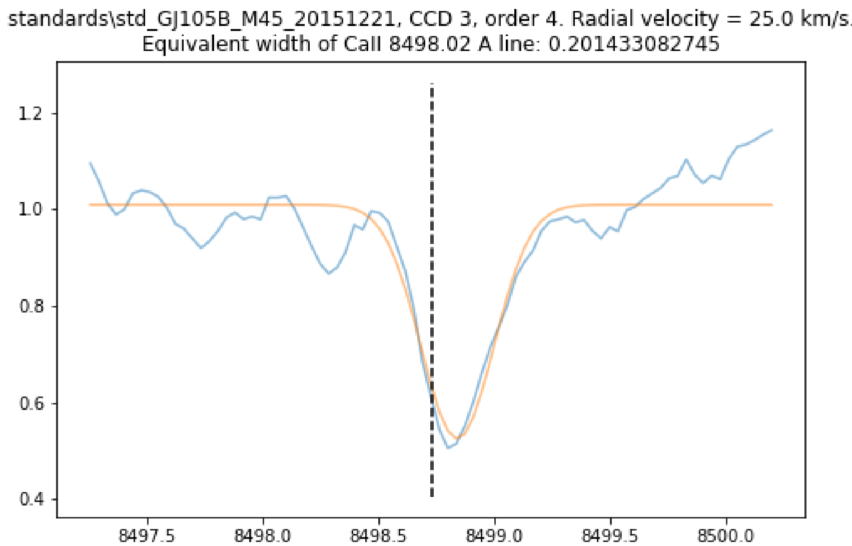

Fig 7. Equivalent width measurement of a star's CaII 8498.02 Å line corrected by the star's radial velocity.

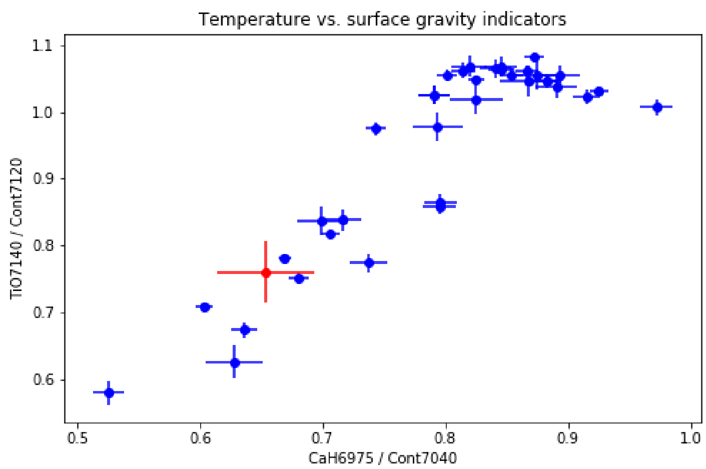

Fig 8. Plot of temperature vs. surface gravity indicators for standard stars (in blue) and a young template star (in red).

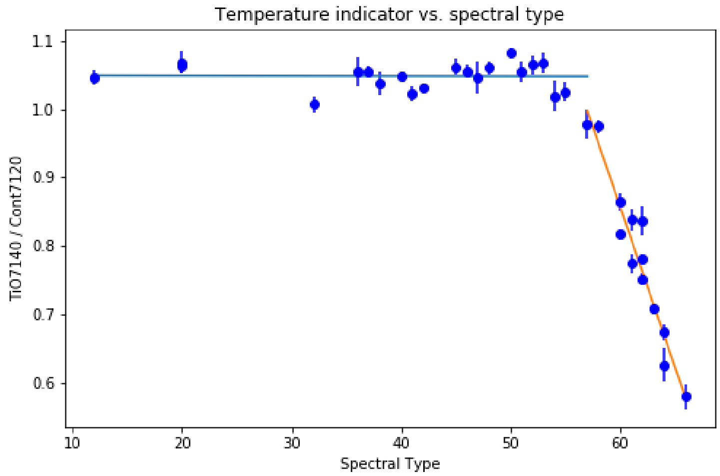

Fig 9. Plot of temperature indicator vs. spectral type for the standard stars. The blue line is a fit of the stars of spectral type O to late K-type stars. The orange line is a fit of the stars of spectral type of late K through M.

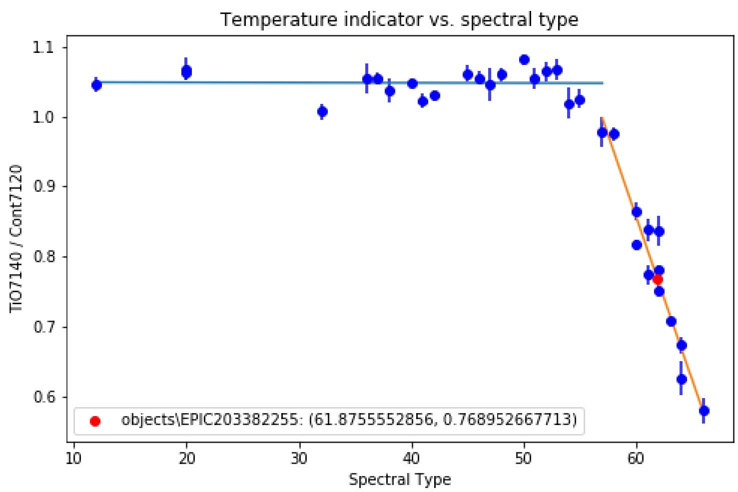

Fig 10. Plot of temperature indicator vs. spectral type for the standard stars. The green star was classified as an M2-type star based on its TiO ratio and the fit line of TiO ratio vs. spectral type for late K through M-type stars.

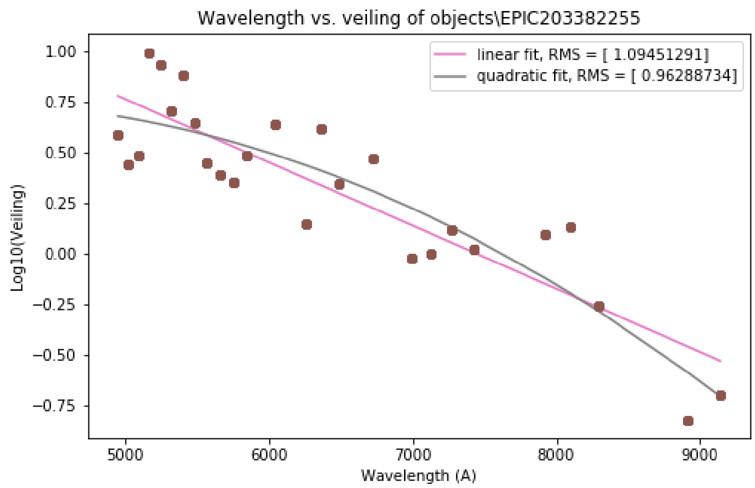

Fig 11. Plot of wavelength vs. veiling of an object star excluding outlier veiling values.

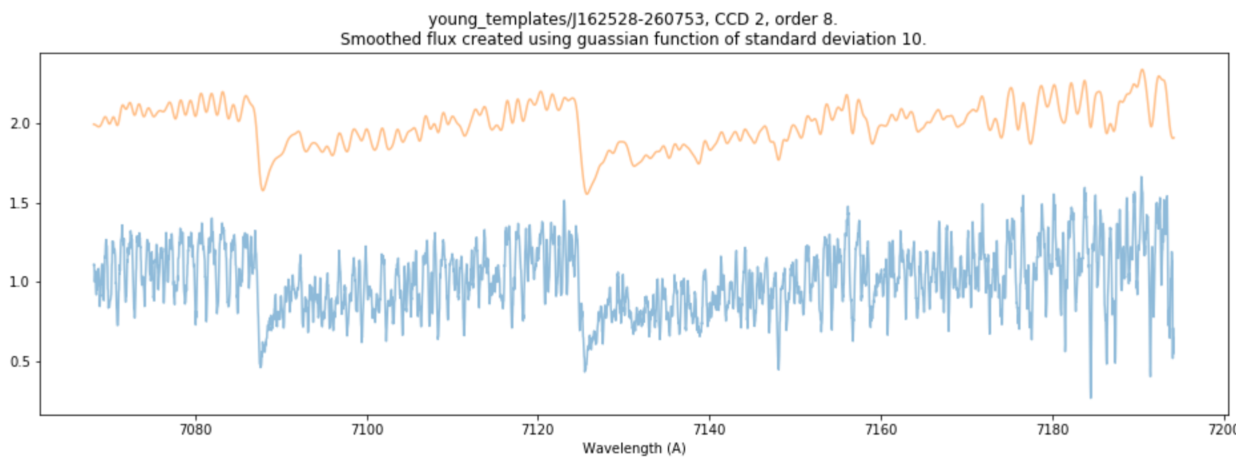

Fig 12. Plot of original spectrum in blue and a smoothed version of the spectrum in orange.

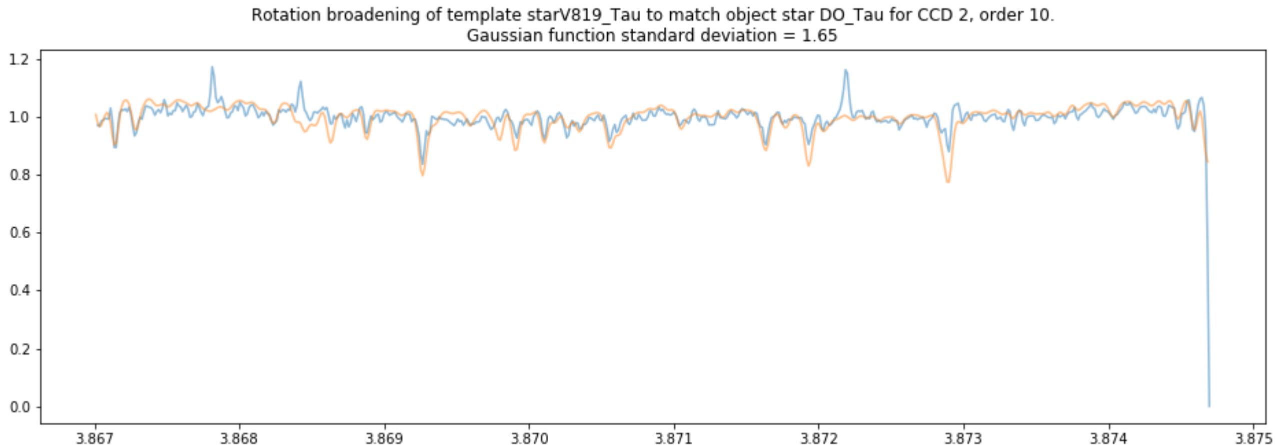

Fig 13. Plot of rotation broadening of a template star (in orange) to minimize chi-square error with an object star (in blue) using a Gaussian function convolution with standard deviation of 1.65.

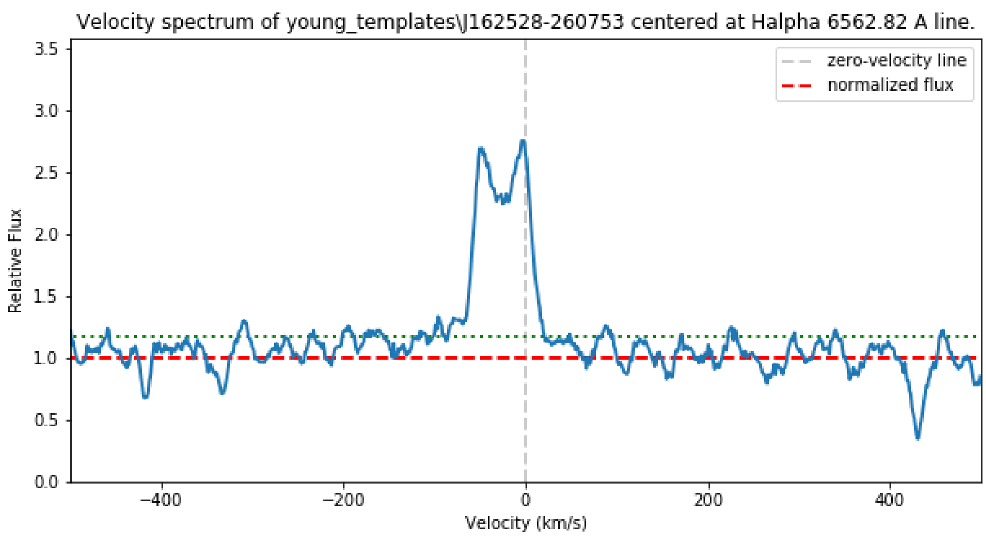

Fig 14. Plot of velocity spectrum of a star with H-alpha line emission. The dotted green line represents 10% of the maximum flux in the plotted region of spectrum.

Conclusions and Future Work

While all the general data analysis tools to determine the stellar and accretion properties of T Tauri star systems were included in the IPython notebook software infrastructure, further development can be done to improve the functionality. More extensive testing of the modules, especially with the use of object stars, can identify areas of improvement where certain modules may have to adapt with more unusual spectrum behaviors. Additionally, more work can be done to further integrate individual modules with others, such as fully implementing the option to exclude all emission and/or strong atmospheric bands regions from any spectrum analysis calculations if desired.

Along with general improvements to the overall structure of the IPython notebook, certain modules can be further developed to analyze spectra more accurately. In the module for modelling spectral lines of a star, a Gaussian function is used to model the spectral line. The addition of the option of modelling spectral lines using Lorentzian functions instead of Gaussian functions for certain emission lines can improve the accuracy of modelling spectral lines for strong emission lines such as H-alpha lines in certain stars. Another module that can be further developed is the rotation broadening. As of now, the module returns only the standard deviation of the Gaussian function used for the template spectrum convolution that most closely matches the object star spectrum, so a function can be implemented to convert this standard deviation into a vsini measurement. Additionally, the Gaussian function used for convolution with the template spectrum in the rotation broadening function can be updated to a function that more accurately models the star by accounting for the limb darkening phenomenon that occurs with stars (the so-called “Gray” rotation profile). Nonetheless, this software is ready to be applied to the extensive library of existing Keck/HIRES spectra to further understand young star systems.

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