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A NEW METHOD FOR FINDING EXOPLANETS

by

John I. Bailey, III

A senior thesis submitted in partial fulfillment
of the requirements for the Honors Program

The University of Alabama in Huntsville

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HONORS RESEARCH PROJECT

APPROVAL

Name of candidate: John Ira Bailey, III

Department: Department of Physics

Degree: Bachelor of Science in Physics
Bachelor of Science in Mathematics

Full title of project: A New Method for Finding Exoplanets

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THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

ABSTRACT

A NEW METHOD FOR FINDING
EXOPLANETS

by John I. Bailey, III

Dr. Russel White, Advising
Department of Physics

The unexpected properties of many of the 228 known exoplanets, such as gas giants very near their parent star, have challenged basic theories of planet formation. Testing new theories requires characterizing the basic properties of yet undiscovered young planets – planets that orbit young stars. The first step in this endeavor is to find young planets. Accordingly, we are conducting a radial velocity survey of young stars to search for young planets. To overcome the observational challenges that young stars present, we are pioneering high-precision radial velocity measurements at infrared wavelengths. My work has been the development of a software suite that calibrates our observations, extracts spectra from these observations, and models these spectra to determine the basic stellar properties of observed stars. One of the key properties is the radial velocity of the star, in which we can search for periodic variations caused by an orbiting planet. The results of this analysis are presented here. This work will culminate in the first high-precision infrared radial velocity search for young planets.

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I. INTRODUCTION AND MOTIVATION

Of the 228 exoplanets[1] discovered thus far, a great many of them possess properties very different from the planets in our solar system. One of the most unexpected discoveries was the presence of gas giants (i.e. Jupiter-like planets) at small (<1 AU) separation from their host stars. In fact, more than 20 percent of the known exoplanets are these so-called hot-Jupiters (Butler et al. 2006). The prevalence of planetary systems with characteristics so different from out own has resulted in a major overhaul of planet formation theories. These new theories still favor formation at wide separations, but suggest that the planets migrate inward through tidal interactions with remnant disk material or other planets (Lin et al. 1996; Adams & Laughlin 2003). To test these new theories it is critical that planets be identified around young (age <20 Myr) stars. Such a search will place experimental constraints on the timescale for this migration and of planet formation in general.

Despite the scientific value of such a search, one has yet to be conducted. This is largely due to the optically faint and chromospherically active nature of young stars. Both of these characteristics make obtaining the precision measurements necessary to detect an orbiting planet difficult using present *optical* techniques (Paulson & Yelda 2006). We expect to overcome these with a novel *infrared* observational technique and a thorough computational analysis of the gathered data.

This thesis documents a portion of our research conducted over the past two years and details the results thereof. A description of our research methods, along with a general description of our ongoing research, is given in Section II. In it we develop the prescription needed to carry out scientific analysis on our gathered data. In Section III we then present the implementation of this prescription, the Young Stars Analysis Suite. In closing, we highlight some of the results of my research and detail where our work is headed over the next few months.

[1] See http://www.exoplanets.org for the current number.

II. DESCRIPTION OF METHOD

By far the most effective method for identifying extrasolar planets has been precise measurements of stars radial velocities (RV) (see Butler et al. 2006). The gravitational tug of a planet as it orbits a star will induce periodic changes in the star's RV. By monitoring these periodic changes one can determine the planets orbital period and set limits on its mass.

The technique we develop here is an extension of this widely used and successful method. Unfortunately, current surveys are not targeting young stars because they are on average more distant than type A stars, and thus fainter. Moreover their increased chromospheric activity has been seen to cause significant (~100 – 250 m/s at 5500 Å; Hatzes 2002) shifts in measured RVs, thereby mimicking a planet.

Our search, the first of its kind, will mitigate these observational challenges by observing in the infrared (19,850-23,900 Å; primarily focusing on 22,170 – 22,500 Å). As young, cool stars are effectively brighter in the infrared, observing in this regime maximizes incident flux. More significantly, the contrast between photosphere and star spots is reduced approximately fivefold (Terndrup et al. 1999). As the RV noise induced by star spots shows an approximately linear relation with the amplitude of photometric variability (Saar & Donahue 1997), we can reasonably expect RV noise to be limited to a manageable level of 20–50 m/s.

Observations and Sample

We measure these RVs from a series of infrared spectroscopic observations. The observations have been obtained using the NIRSPEC instrument on the W. M. Keck II telescope on Mauna Kea in Hawaii. NIRSPEC is a cross-dispersed infrared echelle spectrograph capable of obtaining high dispersion (R ~24,000) infrared spectra on its 1024 x 1024 pixel InSb detector. Observations have been made in pairs at two locations along the slit. Collecting observations this manner provides a nearly simultaneous measurement of sky emission and detector bias for both images.

With these spectra, our observational goal is to achieve a RV precision limited only by turbulence in the atmosphere (~20 m/s; Campbell 1983). This precision would be sufficient to detect the majority of known exoplanets (**Error! Reference source not found.**). Additionally, the statistical distribution of known exoplanets suggests the sample should contain approximately five extrasolar planets, and likely one hot Jupiter (Butler et al. 2006).

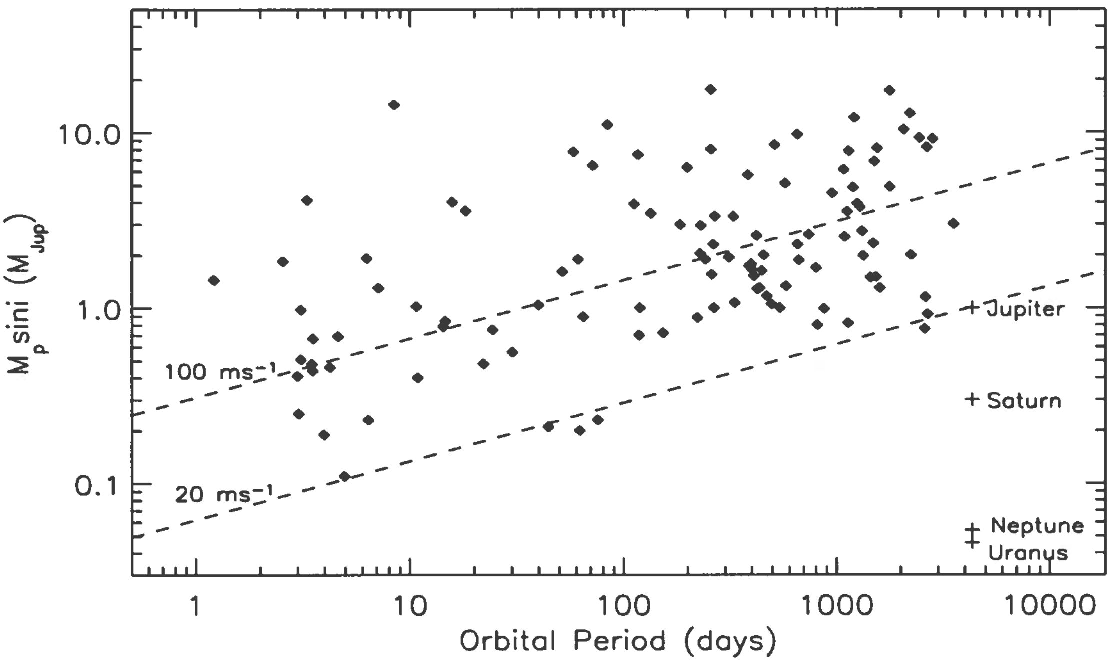

Figure 1 Extrasolar planet mass (msini) versus orbital period for all known extrasolar planets. The masses of gas giant planets in the solar system are shown for comparison, plotted at Jupiter's orbital period. Planets above the dashed lines are ones that would be detectable around a 0.5 M▯ star with precision of 100 m/s, and with the expected telluric limiting precision of 20 m/s.

The primary sample we have been surveying for planets consists of ~60 young, late-K and M type, slowly rotating stars in four nearby T associations (Taurus, Upper Scorpius, Beta Pic, and TW Hydrae). In addition to these, we observe A type, rapidly rotating stars and stars with well determined radial velocities. These latter two classes of star are used in the calibration process and for determination of our method's precision, respectively.

Reduction

The spectra obtained are a product of a number of factors. The intrinsic spectrum emitted by the star is both broadened by rotation about its axis and Doppler shifted by its radial velocity. On passing through the atmosphere, the star's light is both filtered through the Earth's atmosphere and contaminated with light from night sky emission lines. The amount of starlight filtered is airmass (i.e. elevation) dependant. It is this light that is then dispersed by NIRSPEC and incident on its detector, which is composed of many pixels of varying sensitivity. The resulting image is a convolution of the incident light with the detector's spectral point-spread function (PSF) plus some bias inherent to each pixel.

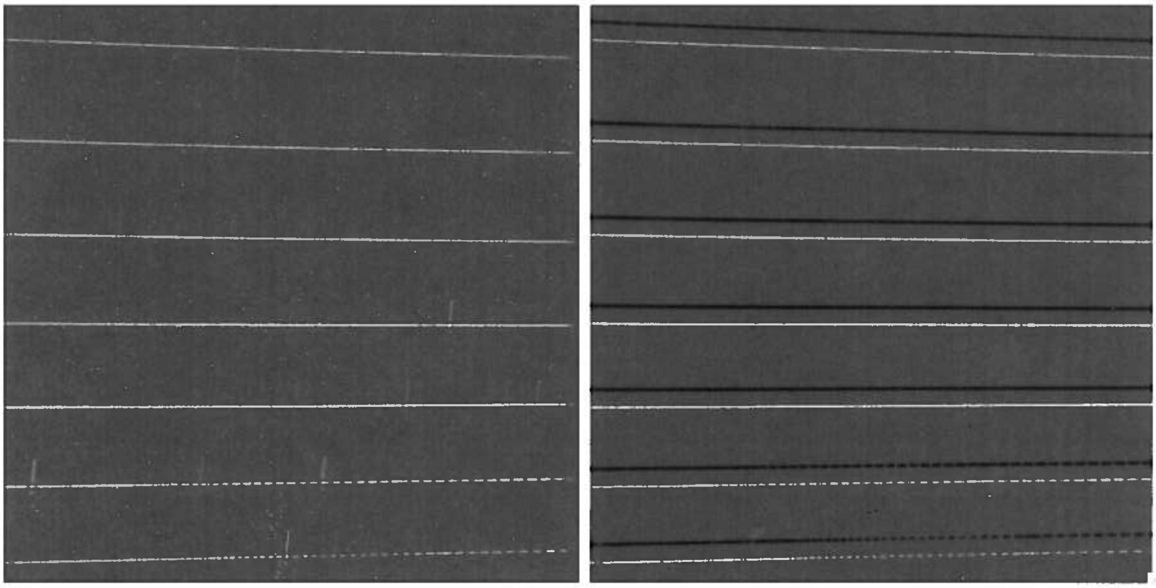

Figure 2 A raw (left) and a reduced (right) NIRSPEC observation of DN Tau.
The night sky emission lines present in the raw observation are effectively removed by subtracting the companion observation; this causes the negative spectrum seen in the reduced image.

The observed image must be converted into a one-dimensional spectrum in order to extract meaningful data. One simplistic approach is to simply divide the image by a flat field to account for the varying sensitivity of the detectors pixels and then simply total the flux along the spatial dimension. This method can be improved by first subtracting off both light from night sky and the detector bias. Figure 2 shows the results of sky subtraction followed by flat fielding. This is possible as our observations are made in pairs: essentially all of the measured flux on the unused half of the detector comes from the night sky and detector bias.

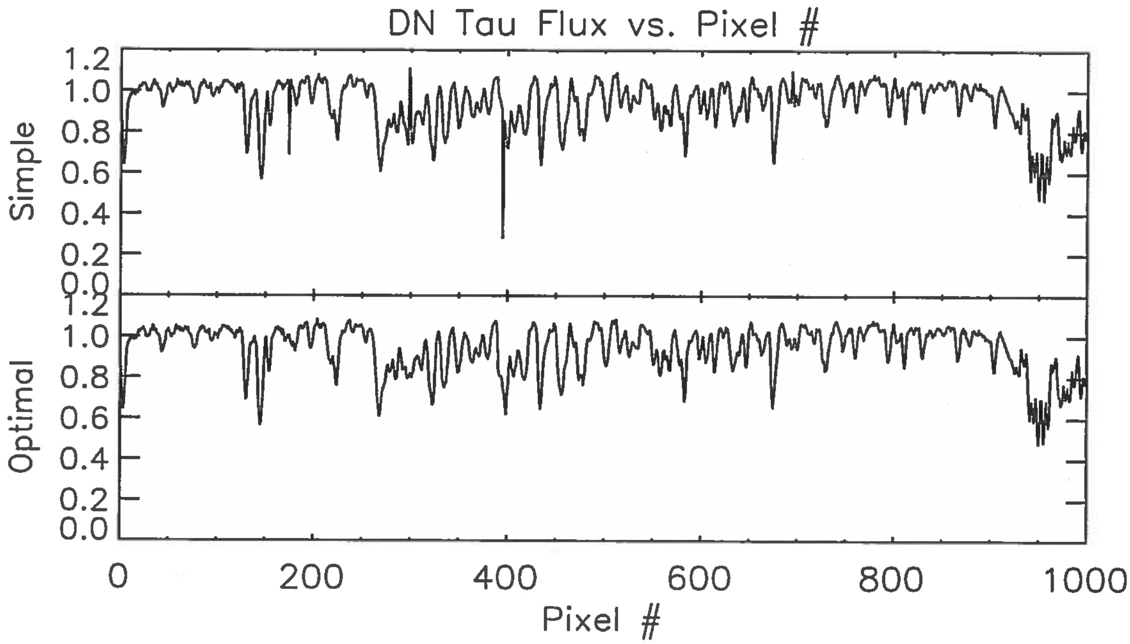

Figure 3 Sample extracted spectrum of DN Tau.
The simple extraction simply sums the counts versus wavelength and is therefore sensitive to errors from cosmic rays and bad pixels. The optimal extraction eliminated these by assuming the spectral profile varies slowly with wavelength.

Unfortunately, this method is still highly sensitive to cosmic ray impacts and defective pixels on the detector. We further improve upon it by making use of the variance-weighted spectral extraction method described by Horne (1986). The basic idea of this methodology is that the spectral profile should vary smoothly with wavelength, allowing easy identification of deviant pixels and cosmic rays (see Figure 3). The multiplicity of cross-dispersed echelle spectral orders in a single image and the presence of the negative spectrum caused by subtracting nod pairs necessitate that each image separated into single orders and negative regions masked prior to their extraction. Once extracted, orders are normalized to unity to facilitate comparison.

Modeling

To characterize the star's spectrum, and thereby the radial velocity, we construct a model of the observed spectrum using mathematical descriptions of the various phenomena described (e.g. stellar rotation, Doppler shift) as well as template spectra for the telluric spectrum and the star itself. For the telluric spectrum we use an ultra-high resolution reference spectrum from the Kitt Peak National Observatory's Fourier Transform Spectrometer. For the star, while not precisely known, the spectral type provides sufficient information to place limits on its emitted spectrum; thus we use a number of synthetic spectra spanning the range of temperatures appropriate for our sample. A collaborator, Dr. Travis Barman, following a method similar to Allard et al. (2000), has precomputed synthetic spectra for this purpose.

It is critical that the wavelength solution and PSF of the detector be properly characterized as any mischaracterization can significantly alter the determined RV. To ensure these parameters are well characterized, we first model the spectra of hot, rapidly rotating stars in our sample. Since these stars exhibit what is essentially a smooth continuum, rotational broadening and Doppler shift effects are essentially absent. We are therefore free to model the star omitting such effects; the resulting model thus serves to characterize the wavelength solution and PSF alone.

Coordination

The significant size of our dataset (~900 observations) poses a challenge in itself. Each of the factors described must be accounted for in each observation. If executed individually, determining the radial velocities for a single epoch would require significant time beyond that needed for a collective analysis. Manual execution would require observational logs to be referenced for each observation in the sample to determine the appropriate calibration information. Those raw observations would then need to be located and their spectra extracted and modeled. Furthermore, as each observation's wavelength solution is based upon the spectral profile and wavelength solution determined from observations of hot, rapidly rotating stars observed on the same night, those observations must also be located, extracted, modeled, and the resulting parameters combined before the star can be modeled. By developing software that can carry out the data reduction while simultaneously managing the entirety of the dataset significant time is saved.

III. IMPLEMENTATION

To measure the RVs of the stars in this large dataset, I have constructed the Young Stars Analysis Suite (YSAS). This software suite is a collection of interlinked routines written in the Interactive Data Language (IDL) programming language. This programming language is in heavy use among astronomers and provides a wide range of useful library functions, such as is catalogued in the Astronomy User's Library[2]. It is capable of cross-platform operation.

YSAS is designed to coordinate processing of a large observational dataset and is able to keep track of calibration information for every observation. By using a combination of simple text configuration files and on-disk organization of raw data, it is able to eliminate much of the tedious and repetitive work necessary to perform scientific analysis on the data. It is capable of performing all of the scientific analysis necessary to completely reduce our raw dataset. Analysis includes order detection, masking, spectral extraction, and spectral modeling for both types of stars in out sample. The major tasks the software accomplishes are discussed below. These include parsing the dataset, extracting the spectra, and modeling the spectra.

Parsing the dataset

Before beginning analysis, YSAS must parse both user-settings and science data into a form it understands. This is made possible via a combination of on-disk organization of raw data, user created text configuration files, and a routine to initialize dataset specific settings and debugging options. When run, YSAS checks for an IDL .sav file in a user-specified location. If YSAS is able to restore the file it does so and analysis may begin; if not, YSAS first reads the calibration data and configuration files[3]. YSAS then stores all of the observational data into data structures, associating calibration information with observations as it does so. It should be noted that the individual observations are *not* loaded into memory; rather relevant header information and the observations file names are stored. YSAS treats each nod pair as an "observation set" and groups these sets together based upon the observed star.

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[2] See http://idlastro.gsfc.nasa.gov

[3] Details configuration instructions for YSAS may be found in the YSAS Users Manual.

Extracting the Spectra

This stage of analysis is carried out using the raw nod pairs of observations. The detection of spectral orders is first performed on each frame in the pair. This is accomplished by fitting user-defined regions containing each of the spectral orders with a Gaussian in the spatial direction. The central maxima of these fits are then fit with a quadratic, thereby identifying the center of the spectral profile along the detector. Pixels beyond 3σ from the central maxima are masked and omitted from further consideration. The images in the nod pair are then subtracted from one another and each divided by the appropriate median flat field (see Figure 2). Each detected order is then extracted using a modified version of the `optspecextr` package,[4] an implementation of the algorithm given by Horn (1986). In the event of an incomplete nod pair, the user has the option of specifying another image to use for removal of sky emission lines and detector bias. A flag in the pair's data structure allows handling these situations automatically.

Modeling the Spectra

As it is necessary to model different types of stars (hot, rapidly-rotating; cool, young), each to a significantly different end (determining the instrumental profile; finding RVs), these tasks are implemented via a general stellar modeling routine, `fit_Spectrum`, and case-specific driver routines. This enables ready selection of what model parameters are to be determined while also facilitating future expansion of YSAS's modeling capabilities.

The model takes as input ten parameters, three of which describe the wavelength solution. Of the remaining parameters, one is used for each of the following: the detector's PSF, the airmass, the stellar feature depth, the star's *v*sin*i*, the star's RV, limb darkening, and a normalization offset. The limb darkening parameter is held fixed at 0.6 in all of our analysis. In addition to the parameters, the model requires both stellar and telluric template spectra. Any combination of these parameters may be varied when searching for a model of an observed spectrum.

Once called, the `fit_Spectrum` attempts minimization of the error between the spectral model and the observed spectrum using the variance-weighted reduced chi-square between the

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[4] Created and maintained by J. Harrington et al. See http://physics.ucf.edu/~jh/ast/software/optspecextr-0.3.1/doc/index.html for further details.

two as a metric. The minimization is carried out by IDL's implementation, `AMOEBA`, of the downhill-simplex minimization method (Nelder & Mead 1965). In order to prevent the method from converging to a minimum, minimization is restated using the optimized variables until the chi-square drops by less than one percent. The following sections detail the two driver routines implemented.

Hot, Rapidly Rotating Stars

The type A stars in our sample are used for determination of the wavelength solution (YSAS assumes a quadratic form) and instrumental profile (assumed to be Gaussian) of the detector. Since these parameters can potentially change over the course of the night, A stars were typically observed twice a night; the parameters obtained from the A star observed closest in time to each young star observation are used in its analysis. As these solutions are used in modeling each observation made on a given night, recomputation each time they are needed would severely increase the computational time. Instead, YSAS is designed to compute and store the parameters the first time they are needed and thereafter only return them, provided the user does not specify otherwise.

The parameters are determined by configuring the general modeling routine, `fit_Spectrum`, in the following manner. The routine is set to omit computation of Doppler shift and rotational broadening of the stellar spectrum since the spectrum is essentially featureless. It is provided with a continuum spectrum as a template for the star's intrinsic spectrum, as this suitably approximates the emitted spectrum. The modeling routine is then set to vary the six remaining model parameters (three for the wavelength solution; one each for the PSF, the airmass, and the normalization offset). The last of these parameters is used to account for any imperfection in the continuum normalization of the observed spectrum.

Young Stars

When modeling a young star, YSAS first gathers all of the extracted spectra for a given star, retrieving (or computing, if need be) the wavelength and PSF parameters for each spectrum as described in the preceding section. A user specified range of synthetic spectra for the star are then retrieved, after which YSAS begins determination of the spectral model. For young stars, determination of the model is done in three stages: the appropriate synthetic spectrum is first determined, followed by the star's $v\sin i$, and then the remaining stellar parameters. In each of these stages the 1st and 2nd order wavelength solution parameters as well as the PSF parameter are held fixed at the values retrieved. The 0th order parameter is allowed to float, using the value retrieved from the wavelength solution as an initial guess in each stage.

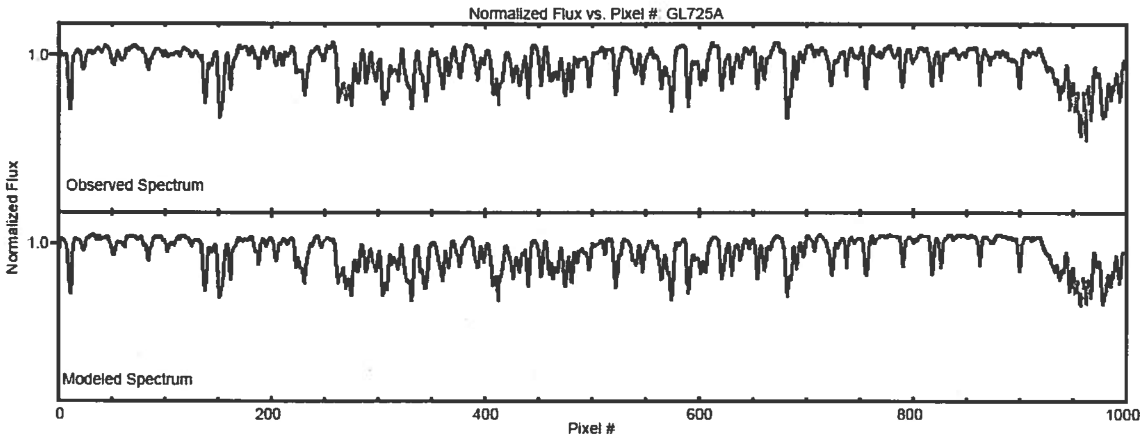

Figure 4 A spectrum and its computed model.
The excellent alignment of the model to the spectrum demonstrates the success of our modeling technique.

In the first stage, `fit_Spectrum` is used to construct an optimal model based upon each of the synthetic spectra. Each observed spectrum is modeled using each synthetic spectrum. The models are computed allowing the parameters for airmass, *v*sin*i*, RV, and normalization to float. The stellar feature depth parameter is held fixed at one for this first step; in remaining steps it is allowed to float. A weighted mean of the best-fit chi-squares is then computed over the observed spectra. The synthetic spectrum with the lowest mean is then used for all further analysis of the particular star. Next, the *v*sin*i* is determined as in Blake et al. (2007). Here we use seven equally spaced values ranging from 1 – 15 km/s. In the final stage, `fit_Spectrum` is configured to hold the *v*sin*i* fixed at the computed value while allowing the five remaining parameters (0th order wavelength solution, airmass, spectral feature depth, RV, and normalization offset) to float. Thus configured, models for each of the star's spectra are computed. Figure 4 shows a example spectrum and its computed model. Finally YSAS computes the Barycentric correction to each of the RVs and returns the result to the user, along with the other model parameters and their chi-squares.

IV. SUMMARY

Presented herein is a prescription for measuring precise RVs of young stars using near-infrared spectra. The technique has the potential to discover recently formed planets, if present. The completion of the Young Stars Analysis Suite is a major milestone in human-kind's ongoing search for extrasolar planets. The first discoveries of young planets will not only help constrain planet formation theories, but will also further address the potential for life in the universe, as the conditions for life are likely set-up during the planet formation process.

In addition to measuring RVs, YSAS also determines the stellar spectral type and rotational velocity of stars in our sample. Our tests have found it capable of managing a large subset of our data while carrying out analysis on the same. Initial analysis of RV standards in our sample has shown RVs with a noise of approximately 40 m/s within an observing run. This is more than a magnitude less than the amplitude of variations induced by many hot Jupiters. We fully expect to further improve our precision as we refine and extend processing, and with luck will discover the first known young exoplanet.

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