

Measuring Radial Velocities with the Goodman Spectrograph at SOAR

S. D. POINTS,¹ B. C. QUINT,² AND J. ELIAS²

¹*National Optical Astronomy Observatory
Cerro Tololo Inter-American Observatory
Casilla 603*

La Serena, Chile

²*SOAR Telescope
Casilla 603
La Serena, Chile*

ABSTRACT

This document is designed to provide advice on how to obtain, reduce, and measure radial velocities with the Goodman Spectrograph on the SOAR telescope. In the following examples, we examine radial velocity data obtained using the Goodman Spectrograph of the radial velocity standard, HD 177409. The first set of data were obtained using the 12001mm⁻¹ grism and the 1'' slit during a five night observing run beginning on 08 June 2017. The second set of data were obtained using the 12001mm⁻¹ grism and the 0.''45 and 1'' slits during the night of 25 June 2018.

1. INTRODUCTION

The accurate and precise measurement of radial velocities is of fundamental importance in observational astronomy. For example, measurements of the radial velocity of an object over time can be used to determine if the object has a visually unresolved stellar or sub-stellar companion. The ability of a spectrograph to measure the radial velocity of an object is dependent on the resolving power of the spectrograph which is a function of the disperser and the slit width. In this document we describe procedures on how to obtain, reduce, and measure the radial velocities of objects using the Goodman Spectrograph at the SOAR 4.2-m telescope on Cerro Pachón, Chile. We discuss observing tactics in §2. We describe the data and the basic data reductions in §3 and §4, respectively. We provide comments on obtaining an accurate wavelength calibration in §5. We investigate two different methods to obtain the radial velocity of an object in §6 and summarize our results in §7.

2. OBSERVING STRATEGY

In order to obtain accurate radial velocities with Goodman at SOAR one should plan to take the necessary daytime calibrations in addition to observing the object of interest in a systematic fashion. Precise radial velocities with Goodman (or any other spectrograph) require that the comparison lamp spectra and target spectra be taken without moving any components inside the spectrograph. The procedures below ensure that the required level of stability is provided.

2.1. Daytime Calibrations

For the daytime calibrations, you should take bias frames, dome flats, and comparison lamp spectra for your observing program. One should generally use the same readout parameters for all of the data. For example, Goodman has different readout speeds for each camera that also depend upon the CCD binning that one chooses. Dome flats and comparison lamp spectra should be taken for each slit and grating configuration. It is also suggested that one takes a variety of daytime comparison lamp spectra (e.g., HgAr, HgAr+Ne, CuHeAr, FeHeAr, or CuHeAr+FeHeAr).

2.2. *Nighttime Observing*

The observing procedure we used to obtain radial velocity measurements is summarized below. Precise radial velocities with Goodman (or any other spectrograph) require that the comparison lamp spectra and target spectra be taken without moving any components inside the spectrograph. The procedures below ensure that the required level of stability is provided.

2.2.1. *Align the Target on the Slit*

Align the target on the slit using either the Goodman Acquisition Camera (GACam) or by using the classical technique of taking a field image, a slit image, and computing an offset. The instrument support scientist can advise you on how to do this. The GACam should be used for objects that are brighter than $V \leq 18$ mag. Nothing should be moved after this step. The grating, camera, and slit need to be in the same position after aligning the target on the slit for the comparison lamp spectrum and the object spectrum.

2.2.1.a *Classical Acquisition*

This section describes the classical techniques to align a target on the slit using Goodman.

- Select “Withdraw Mask” in the cyan Mask Box. This removes the slit from the beam.
- Select “Image Mask” in gray Mask Imaging Box. This removes the grating from the beam and sets the camera angle to zero degrees for direct imaging.
- Take an image of the field using a reasonable exposure time.
- Display the acquisition image in the IRAF ds9 window and determine the coordinates of the object using `imexam` and the “a” key.
- Record the pixel values of the object in the “Current Pixel Values” box in the Goodman GUI.
- Select “Insert Mask” in the cyan Mask box.
- Take an image of the slit using a reasonable exposure time.
- Display the slit mask image in the IRAF ds9 window and determine the coordinates of the slit center using the “j” key. It is useful, but not necessary, to always determine the slit center at the same y-pixel value.
- Record the pixel values of the slit center in the “Desired Pixel Values” box.
- Click on the “Calculate Required Offset” box to convert the pixel offsets to an offset in RA and Dec.
- Click on “Apply SOAR Offset” button to move the telescope to the desired position. It is recommended that you inform the telescope operators when you are making a large ($\geq 60''$) so they make sure that the guide star is not lost.
- Take an image of the object through the slit mask using a reasonable exposure time.
- The object should be centered on the slit at the y-pixel value that you entered in the “Desired Pixel Values” box. There are various methods to verify the alignment of the object on the slit mask. One can display the image in the IRAF ds9 window disabling the automatic z-scale by
`> display image.fits zs- zr- z1 = 500 z2 = 2000`
 where z1 and z2 are chosen using values from the data. After the image is displayed you can use `imexam` and the “e” key to look at a contour plot of the object on the slit. If the contours look asymmetric, you may want to apply another offset. You can also use `imexam` and the “j” key to determine the x-pixel value of the slit above and below the object. You can then use the “j” key to determine the x-pixel value of your object. By looking at the difference between the slit mask pixel values and the target pixel values, you can calculate how well centered the object is.
- Once the object is centered on the slit mask, select the “Return” button in the “Mask Imaging” box. This will move the grating back into the beam and move the camera angle to the desired values for spectroscopy.

2.2.1.b *GACam Acquisition*

This section describe how to use the Goodman Acquisition Camera (GACam) to align a target on the slit.

- Select “Move In” option under the “Control” menu tab in the GACam GUI to move the Goodman Acquisition camera arm into the beam.
- Make sure that the Goodman slit mask is in the beam.
- Unselect the “Lock Crosshair” option in the GACam GUI.

- Center the GACam crosshair on the slit by using the mouse or the arrow keys on your keyboard.
- Select the “Lock Crosshair” option in the GACam GUI after the crosshair is centered on the slit.
- Unselect the “Lock Slitbox” option in the GACam GUI.
- Move the slit box to the target using either the mouse or the arrow keys on your keyboard.
- Open the “Offsets” option under the “Control” menu tab in the GACam GUI.
- Click the “Compute” button in the “Offsets” window to calculate the necessary offset.
- Click the “Apply” button in the “Offsets” window to apply the offset. You should see the object move to the center of the crosshair.
- You can fine tune the centering of your object on the crosshair by directly applying small offsets.
- Once the object is centered in the crosshair, you can select the “Move Out” option under the “Control” menu tab to move the GACam arm out of the beam.

2.2.2. Mark the Current Telescope Coordinates

After the target is aligned on the slit, ask the telescope operators to mark the current coordinates. We do this because guiding is interrupted when the comparison lamp mirror is placed into the “in” position. We mark the coordinates so the telescope operators can return to the same position after taking a comparison lamp spectrum. To precisely and accurately measure the radial velocity of an object we must return to the same initial configuration.

2.2.3. Take a Comparison Lamp Spectrum

The choice of comparison lamp depends upon what grism and wavelength setup you are using and the desired wavelength accuracy. It should also be noted that different comparison lamps have different times to “warm up” to nominal operating conditions. It is suggested that five (5) comparison lamp spectra be taken when using the PenRay lamps (e.g., HgAr or HgAr+Ne) and three (3) comparison lamp spectra be taken using the hollow cathode lamps (e.g., CuHeAr and/or FeHeAr). Cautious observers should take comparison lamp spectra using as many lamps as possible during daytime calibrations.

Use the IRAF task `imexam` to look at the comparison lamp spectra to make sure that there are enough counts in the emission-lines to determine a wavelength solution. One should also make sure that a sufficient number of emission-lines cover the wavelength range of interest. We present a CuHeAr comparison lamp spectrum in Figure 1. As can be seen in Figure 1, the emission-lines have adequate counts and cover the spectral region of interest.

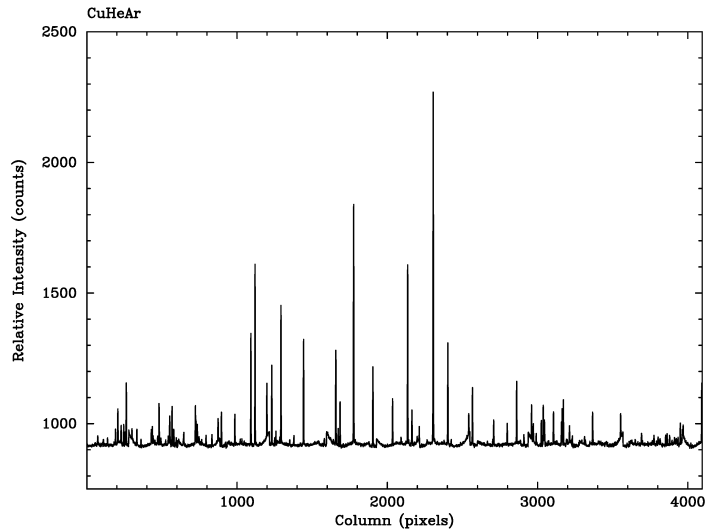


Figure 1. CuHeAr spectrum obtained before observations of the science target. This spectrum was taken using the $0''.45$ slit and 1×1 binning with an exposure time of 180 s.

We note that it can be difficult to identify the features in the CuHeAr and FeHeAr comparison lamps. When possible the observers should also try to take comparison lamp spectra for their spectroscopic setup using the HgAr, Ne, and/or HgAr+Ne sources.

2.2.4. Return to Guiding on the Target

After you are satisfied that the comparison lamp spectrum (spectra) from § 2.2.3 has (have) sufficient counts and wavelength coverage, ask the telescope operator to remove the comparison lamp mirror and resume guiding on the target using the telescope coordinates determined in § 2.2.2.

2.2.5. Take a Spectrum of the Target (≤ 30 min)

If nothing has moved, take a spectrum or series of spectra of the object for up to 30 min (1800 sec). You can take a quick "test" spectrum to make sure that the object is still on the slit or use the GACam. If the object is not on the slit return to § 2.2.1.

To minimize the effects of flexure on the wavelength calibration, we avoided taking taking object spectra for more than 30 minutes without obtaining comparison lamp spectra. We have taken measurements of slit and camera position repeatability while the Nasmyth cage is rotated. These show mostly small and continuously varying positions consistent with the expectations of flexure. However, on some occasions these measurements showed a onetime jump. By taking lamps before and after, and comparing the values, jumps in position can be ruled out. In the event of a rare jump, the data would be discarded.

We reiterate that the observer should not move the slit or change the camera and grating angles at any time after the object was initially centered on the slit. Moving any of these optical elements changes the dispersion solution of the spectrum and requires that the observer start again to obtain an accurate radial velocity.

2.2.6. Take another Comparison Lamp Spectrum

Take a comparison lamp spectrum using the same setup that you used in § 2.2.3. You should examine the comparison lamp spectrum to make sure that there are sufficient counts and emission-lines to determine the wavelength solution. Furthermore, you should compare the lamp spectrum that you just obtained with the lamp spectrum that you obtained in § 2.2.3 to make sure that there have been no major shifts of the emission lines that may indicate that something moved between exposures. In Figure 2 we show two comparison lamp spectra of the CuHeAr hollow cathode taken before and after object spectra were obtained. The comparison lamp spectra were taken approximately 25 min. apart and show no substantial shift along the dispersion direction.

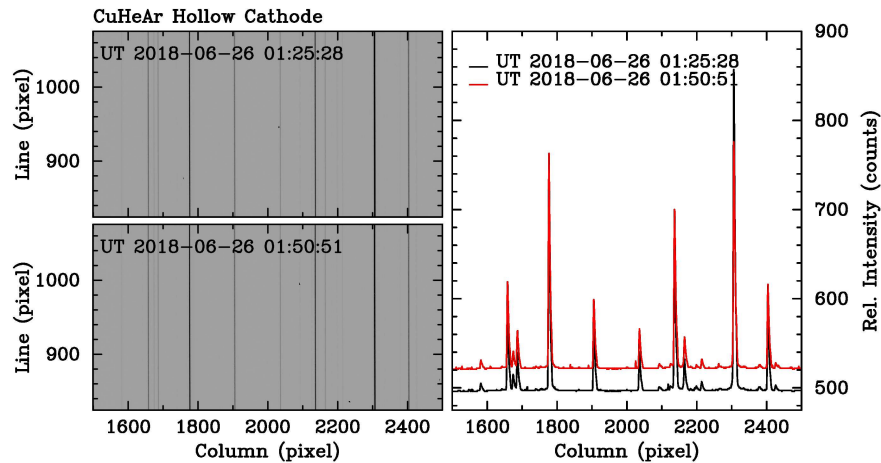


Figure 2. *Left:* Two dimensional CuHeAr comparison lamp spectra taken on 26 June 2018. These spectra were taken before and after the object spectra were taken. *Right:* One dimensional CuHeAr spectra extracted from the two dimensional images shown on the left. The background level of the comparison lamp spectrum taken after the object spectra has been shifted in the y-direction by 25 counts. It should be noted that there is no substantial shift of the emission-lines along the dispersion (x-pixel) direction, indicating that there were no instrument jumps or anomalies

Guiding is turned off when one takes a comparison lamp spectrum. If you want to continue to observe the same object you may need to realign the object on the slit.

2.3. Repeat the Above Steps for a Radial Velocity Standard

In addition to observing our target, we took spectra of a radial velocity standard star in the same setup for the target in order to calibrate the radial velocity zero-point. In this case the radial velocity standard is the target.

3. DATA

We examined spectra of the radial velocity standard star, HD 177409, with the Goodman spectrograph and the 1200 l mm^{-1} grism using archival data from 2017 June and engineering data from 2018 June. The archival data from 2017 June were obtained during five consecutive nights from 2017-06-08 through 2017-06-12 using the $1''$ slit. We also obtained data toward this target during the night of 2018-06-25 using both the $1''$ slit and the $0''.45$ slit. We present a summary of the observations in Table 1.

Table 1. SOAR Goodman Radial Velocity Observations

Object	Obs. Date (UT)	Obs. Time (UT)	Grating	Slit Width (arcsec)	Position Angle (deg)	Exposure Time (sec)
HD 177409	2017-06-09	09:34:30	1200 l mm^{-1}	$1''$	0	150
HD 177409	2017-06-10	08:20:51	1200 l mm^{-1}	$1''$	0	150
HD 177409	2017-06-11	08:38:56	1200 l mm^{-1}	$1''$	0	150
HD 177409	2017-06-12	09:00:43	1200 l mm^{-1}	$1''$	0	150
HD 177409	2017-06-13	10:29:31	1200 l mm^{-1}	$1''$	0	150
HD 177409	2018-06-26	01:12:08	1200 l mm^{-1}	$1''$	278	150
HD 177409	2018-06-26	01:15:04	1200 l mm^{-1}	$1''$	278	150
HD 177409	2018-06-26	01:29:38	1200 l mm^{-1}	$0''.45$	278	600
HD 177409	2018-06-26	01:40:04	1200 l mm^{-1}	$0''.45$	278	600
HD 177409	2018-06-26	03:25:26	1200 l mm^{-1}	$0''.45$	315	300
HD 177409	2018-06-26	03:37:28	1200 l mm^{-1}	$1''$	315	180
HD 177409	2018-06-26	03:41:19	1200 l mm^{-1}	$1''$	315	150
HD 177409	2018-06-26	05:33:31	1200 l mm^{-1}	$1''$	356	90
HD 177409	2018-06-26	05:37:27	1200 l mm^{-1}	$1''$	356	90
HD 177409	2018-06-26	05:45:08	1200 l mm^{-1}	$0''.45$	356	300
HD 177409	2018-06-26	05:50:54	1200 l mm^{-1}	$0''.45$	356	300

4. BASIC DATA REDUCTION

In this section we describe how we prepared our data to make RV measurements. We used common IRAF tasks to perform the basic reductions before extracting the target spectra and their associated wavelength calibration lamp spectra. These basic reductions include trimming the images, creating a master bias frame, bias-subtracting the images, creating a master flat-field, and flat-fielding the object spectra.

After the basic reduction steps were completed we used the `apall` task in IRAF to find the spectrum, define the extraction window and the background windows, trace the spatial profile of the spectrum, and sum the spectrum within the extraction window and subtracting the sky. After the one dimensional spectra were extracted from the two dimensional spectral images, we extracted a one dimensional spectrum from the appropriate calibration lamp exposure using the identical aperture and trace that were used for the object spectrum. We discuss the wavelength calibration of these data in more detail in § 5.

As mentioned above, this guide is primarily concerned with measuring the radial velocity of an object using the Goodman spectrograph. A detailed explanation of the reduction steps can be found in the documents listed below if the reader needs a review.

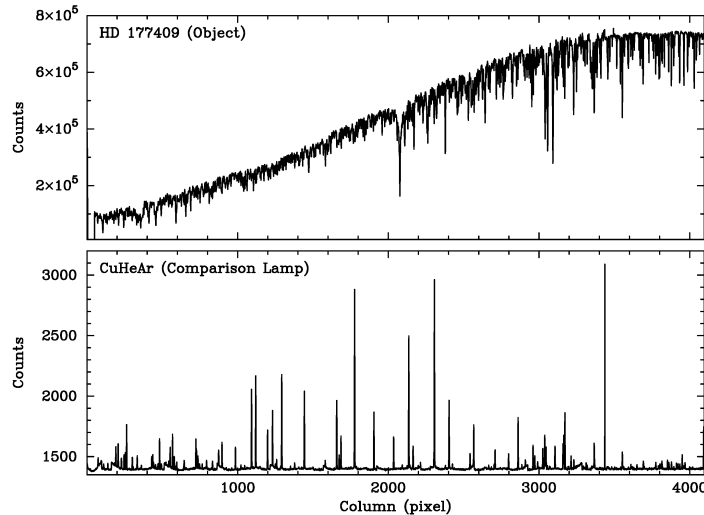


Figure 3. *Top:* Extracted spectrum of the radial velocity target, HD 177409. *Bottom:* CuHeAr comparison lamp for the wavelength calibration of the target. The comparison lamp spectrum was extracted using the parameters as the target.

- *A User’s Guide to CCD Reductions with IRAF*¹ by Phil Massey
- *A User’s Guide to Reducing Slit Spectra with IRAF*² by Phil Massey, Frank Valdes, and Jeannette Barnes

5. WAVELENGTH CALIBRATION

Wavelength calibration is one of the most important reductions stage when measuring radial velocities and merits a more detailed discussion than that presented in §4. For most radial velocity measurements we use the CuHeAr and/or FeHeAr hollow cathode lamps. These lamps should provide adequate wavelength coverage for any instrument setup.

We obtained our line lists for the CuHeAr hollow cathode lamp from two sources: (1) the National Institute of Standards and Technology (NIST) database and/or (2) the IRAF Spectral Atlas webpage. These two resources can be found at the following URLs:

- https://physics.nist.gov/PhysRefData/ASD/lines_form.html
- <http://iraf.noao.edu/specatlas/>

If you have downloaded the spectral line data from NIST, you will need to sort the list to include only lines that are strong and have high transition probabilities. This is because the spectral line information from the NIST database contains every transition for the elements in question. Spectral line information downloaded from the NOAO spectral atlas, however, contains known lines that are visible in most comparison lamps and does not need to be edited.

After you have a line list for your data, you will need to determine the wavelength solution for your data. A common way to do this is by using the IRAF `identify` task. This task allows you to fit a function to a matched list of pixel coordinates and wavelength coordinates for your data. In general, it is good practice to fit the function of your choice to the matched list and increase the order of the function and add or delete fitted lines until the RMS error of the dispersion solution is ≈ 0.1 pixel. The RMS error for the `identify` task is given in Angstroms.

In our example, we are using the 1200 l mm^{-1} grating that has dispersion of $\approx 0.31 \text{ \AA pixel}^{-1}$ in the “M2” setup. Therefore, a 0.1 pixel RMS would be a $\approx 0.03 \text{ \AA}$ RMS error and the wavelength coverage is from $4200 \text{ \AA} - 5500 \text{ \AA}$. We begin using the `identify` task to find a few of the strong, isolated lines that cover the entire wavelength range in this spectrum. After we obtained a preliminary fit of the dispersion solution using the strong lines, we located additional features in the spectrum using the line list based on the NOAO spectral atlas. Once the additional features were identified, we re-fit the dispersion solution and present the results in Figure 4. As seen in Figure 4, many of the lines

¹ <http://iraf.noao.edu/iraf/ftp/iraf/docs/ccduser3.ps.Z>

² <http://iraf.noao.edu/iraf/ftp/iraf/docs/spect.ps.Z>

that are detected are relatively weak or blended with other features in the spectrum. Consequentially, the RMS error on the fit is $\sim 0.17\text{\AA}$ or ~ 0.5 pixels.

We can improve the error on the fit if we delete some of the weaker, blended, or mis-identified features from the fit. In practice, we opt to delete from the fit all features that have a residual greater than 0.1\AA . As seen in Figure 5, we have improved upon the dispersion solution for the CuHeAr lamp by deleting features with high residuals. There are still 36 features identified in the comparison lamp spectrum that cover the full dispersion range. Furthermore, the RMS error of the fit is 0.03\AA (~ 0.1 pixel). Now that the comparison lamp spectrum has a well-fit dispersion solution, we can assign that dispersion solution to the corresponding science spectrum using the IRAF task `refspectra`. In the case of long science exposures where a pre- and post-observation comparison lamp spectra have been obtained for the target, one can use both comparison spectra after making the proper adjustments to the `refspectra` task.

Once the dispersion solution has been determined for the first comparison lamp spectrum, you can use the `reidentify` task in IRAF to copy that solution to your other comparison lamp spectra. Over the course of a night, you should expect some flexure and movement of the slit. To perform the `reidentify` task, you may want to calculate the maximum shift of the comparison lamp features and enter that value in the `reidentify` parameters. In order to ensure that our systematic errors are the same, we require that the same features are present and used in each of the comparison lamp spectra.

After all of the target spectra have a dispersion solution, the data should be linearized using the IRAF task `dispcor`. For the 1200 l mm^{-1} grism M2 setup and the CCD ROI mode set for spectroscopic 1×1 pixel binning, the `dispcor` task should give you results that the starting wavelength is $\approx 4200\text{\AA}$, the ending wavelength is $\approx 5510\text{\AA}$, and the dispersion is $\sim 0.31\text{\AA pixel}^{-1}$.

Once all of the science data have been linearized with `dispcor`, you can run the IRAF task `specplot` to examine the precision of the dispersion solution of the data. Figure 6 shows a modified version of the `specplot` output where each spectrum in a list is offset along the y-axis so one can examine the variations in the wavelength solution. In Figure 6 we show three spectral regions of our HD 177409 data with some of the prominent absorption features labeled. As seen in the figure, the dispersion solution for our data toward HD 177409 are remarkably stable from night to night based on the June 2017 data and over the course of a night based on the June 2018 data. Furthermore, the data show very good agreement from year to year. The noticeable exception to this is the spectrum obtained during the night of 2017-06-13. This spectrum is redshifted with respect to the other data and will be discussed further in §6.2. If more of the radial velocity standard star observations had similar anomalies, it could indicate a problem with the observing techniques or with the wavelength calibration procedure. Given that we seen no evidence of this for data obtained on other nights, we conclude that an optical element of the spectrograph was moved between the target observation and the comparison lamp observation on the night of 2017-06-13 that changed dispersion solution between them.

6. MEASURING RADIAL VELOCITIES

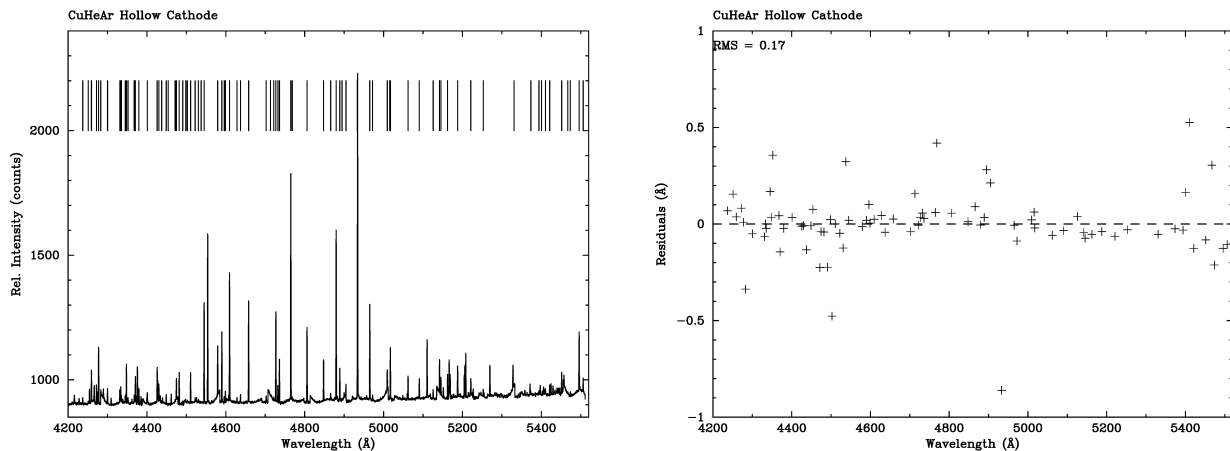


Figure 4. *Left:* Comparison lamp spectrum lines identified using the NOAO spectral atlas. In this example 82 comparison lamp lines were identified. Many of these identified features are either very weak or blended with other lines. *Right:* The residual plot of the identified features. The features were fit using a 4th-order Legendre polynomial. The resulting RMS error of the fit is 0.17\AA (~ 0.5 pixel).

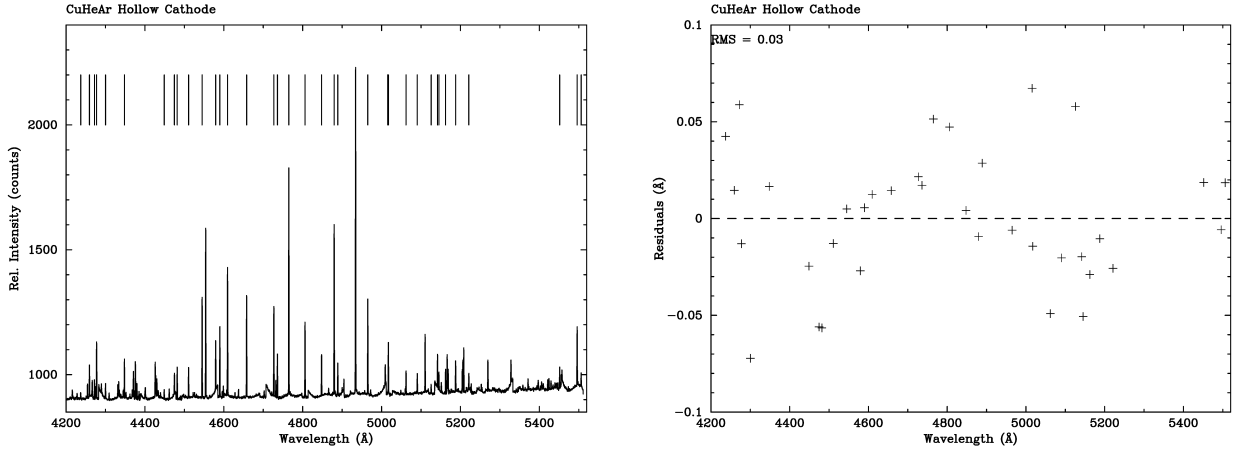


Figure 5. *Left:* Comparison lamp spectrum lines identified using the NOAO spectral atlas. After deleting, weak, blended, or mis-identified features in the fit, 36 stronger and isolated comparison lamp features were identified. *Right:* The residual plot of the identified features. The features were fit using a 4th-order Legendre polynomial. The resulting RMS error of the fit is 0.03\AA (~ 0.1 pixel).

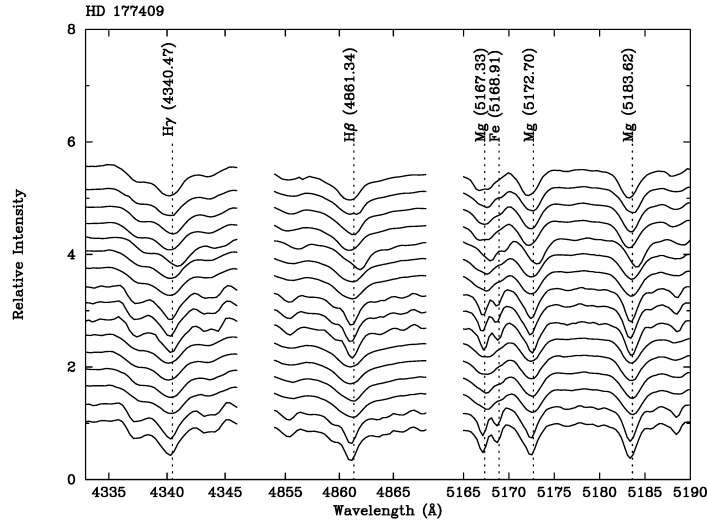


Figure 6. Spectra of HD177409 obtained with Goodman at SOAR with some absorption lines plotted. The spectra are presented in the same order as listed in Table 1 with data from 2017-06-09 at the top and data from 2018-09-26 at the bottom. The spectra are well-aligned, indicating a relatively stable wavelength solution on short and long time scales, except for the spectrum obtained on 2017-06-13.

Now that the data have been processed for the basic reductions (§4) and dispersion corrected (§5), you will be able to measure the radial velocities of your targets.

6.1. Heliocentric Radial Velocity Correction

In order to measure the radial velocities of your targets, you will first need to prepare the data by performing the following tasks to determine the heliocentric radial velocity correction:

- Set the observatory parameters.
- Verify the UT date and time of the observation.
- Update the Goodman FITS header information for the correct epoch.
- Continuum normalize the spectra.
- Correct the spectrum (spectra) for the motion of the observer in the direction of the observation.

To calculate the radial velocities of your targets, you will need to determine the heliocentric radial velocity correction for your targets. The heliocentric radial velocity correction determines the velocity of the observer in the direction of motion. The components of the observer’s motion corrected are those due to the Earth’s rotation, the motion of the Earth’s center about the Earth-Moon barycenter, the motion of the Earth-Moon barycenter about the center of the Sun, and the motion of the Sun relative to some specified standard of rest.

6.1.1. *Set the Observatory Parameters*

The first step to determine the heliocentric radial velocity correction is to set the observatory parameters. This step sets the latitude, longitude, and altitude of the observatory. In our example, the observatory is set to “soar” that gives the following:

- Longitude: 70.734 deg
- Latitude: -30.238 deg
- Altitude: 2738. m
- Timezone: 4

6.1.2. *Verify the Observation Date and Time*

The second step to calculate the heliocentric radial velocity correction for the data is to determine that the “DATE-OBS” FITS header keyword is correct. This FITS header keyword is provided to the Goodman headers by a GPS clock that controlled by the instrument shutter.

6.1.3. *Update the FITS Header Information*

The third step to calculate the heliocentric radial velocity correction is to ensure that the FITS header “EPOCH” keyword is present. The current Goodman FITS header has the “EQUINOX” keyword. The “EQUINOX” keyword is not supported by IRAF. Therefore, the “EPOCH” keyword should be added using the `hedit` task. At the present time, the “EPOCH” keyword should be “2000.”.

6.1.4. *Continuum Normalize the Spectra*

The final step before applying the Heliocentric radial velocity correction to your data is to continuum normalize the data. Using the IRAF task `continuum`, one can fit a function to the the stellar continuum and write an output spectrum that is the ratio between the observed spectrum and the fitted function. We show an example of a continuum normalized spectrum in Figure 7.

6.1.5. *Perform the Heliocentric Velocity Correction*

After the above steps have been completed, you are ready to perform the heliocentric radial velocity correction for the data using the `rvcorrect` task. We present the heliocentric velocity corrections for the data in Table 2.

6.2. *Identify Individual Features in Spectrum to Calculate the Radial Velocity (Method 1)*

A simple way to determine the radial velocity of an object is to identify features in the spectrum and determine the wavelength shift from the rest wavelength. This can be done using the IRAF task `rvidlines`. The object we observed, HD 177409, is classified as a G2V star. Thus, we measured the observed wavelength of prominent Fraunhofer lines identified in the Solar spectrum to determine the radial velocity of HD 177409. We show an extracted spectrum of HD 177409 in Figure 8 with the features used to determine the radial velocity marked. After the positions of the features were marked, the difference between the measured value and the actual value was determined and the observed velocity is calculated. We show the measured features and their determined heliocentric velocities in Table 3. Using the results from Table 3 and shown in Figure 8, we find that the mean heliocentric velocity of HD 177409 is $-11.82 \pm 2.36 \text{ km s}^{-1}$ for the data taken on UT 2018-06-26 at 01:29:38.

After the features were measured in the first stellar spectrum, we then measured the same features in all of our spectra of HD 177409 that used the same configuration, i.e., the 0.45 (3 pixel) slit. We had to omit three of the features (Fe $\lambda 4383.55\text{\AA}$, Mg $\lambda 5167.33\text{\AA}$, and Fe $\lambda 5168.91\text{\AA}$) in the fits to data obtained with the 1" (6.67 pixel) slit because they were blended with nearby absorption lines and were producing velocity results that were not in agreement

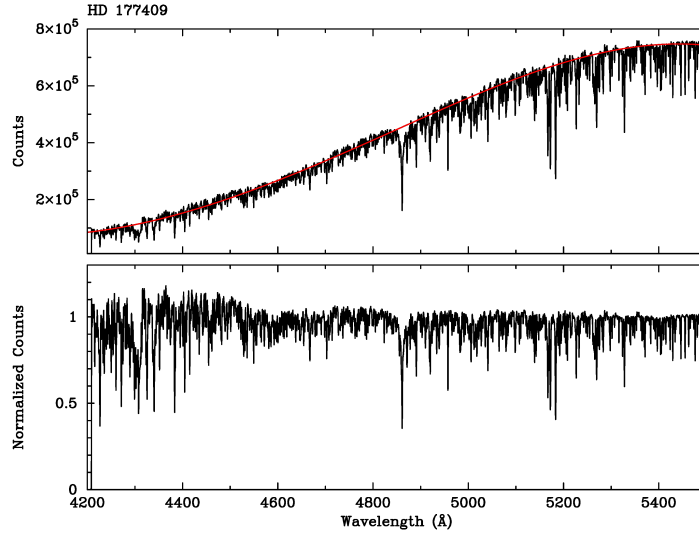


Figure 7. *Top:* Extracted spectrum of the object HD 177409 with the function used to model the continuum shown as the red line. *Bottom:* The output continuum normalized spectrum of HD 177409.

Table 2. SOAR Goodman Heliocentric Velocity Corrections

Object	Obs. Date	Obs. Time	V_{Hel} Cor.
	(UT)	(UT)	(km s^{-1})
HD 177409	2017-06-09	09:34:30	7.3
HD 177409	2017-06-10	08:20:51	7.0
HD 177409	2017-06-11	08:38:56	6.7
HD 177409	2017-06-12	09:00:43	6.3
HD 177409	2017-06-13	10:29:31	5.9
HD 177409	2018-06-26	01:12:08	2.0
HD 177409	2018-06-26	01:15:04	2.0
HD 177409	2018-06-26	01:29:38	1.9
HD 177409	2018-06-26	01:40:04	1.9
HD 177409	2018-06-26	03:25:26	1.9
HD 177409	2018-06-26	03:37:28	1.9
HD 177409	2018-06-26	03:41:19	1.9
HD 177409	2018-06-26	05:33:31	1.8
HD 177409	2018-06-26	05:37:27	1.8
HD 177409	2018-06-26	05:45:08	1.7
HD 177409	2018-06-26	05:50:54	1.7

with isolated absorption features in the spectra. As seen in Figure 9 the $0''.45$ slit provides higher resolution than the $1''$ slit. Given the rest wavelengths of the lines, we can see that the $0''.45$ slit measures the known blue-shift of the absorption features in the object whereas the $1''$ slit tends to measure a redshift for the same lines.

We present the calculated, heliocentric radial velocities of HD 177409 for all of the observations in Table 4 and Figure 10. As seen in Table 4 and Figure 10 the measured radial velocity of HD 177409 varies from -16.20 km s^{-1} to 37.55 km s^{-1} in comparison to the published radial velocity of -9.235 km s^{-1} . We examine the data obtained using Goodman to determine the accuracy and precision of the measured velocities. The errors of the measured velocities

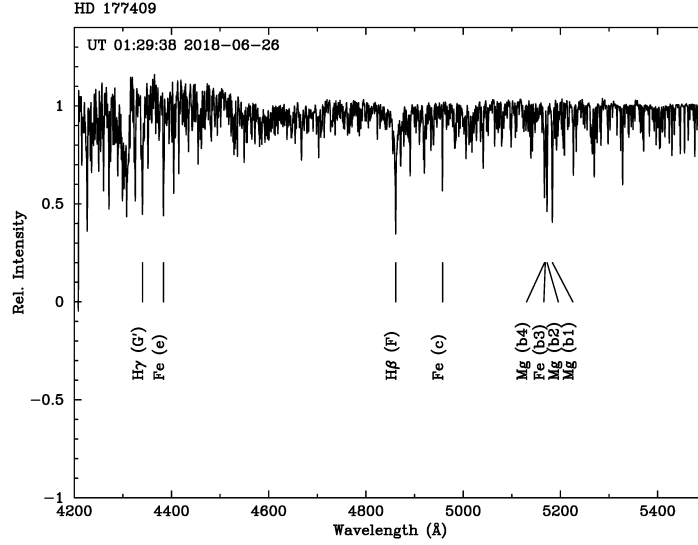


Figure 8. Normalized, continuum-fitted spectrum of HD 177409 with the lines used to determine its radial velocity marked. The line designations in parentheses are the Fraunhofer designations.

Table 3. Absorption Features in the Spectrum

Line ID	Wavelength _{Rest} (Å)	Wavelength _{Obs} (Å)	Velocity _{Helio} (km s ⁻¹)
Hγ (G')	4340.47	4340.2792	-11.23 ± 2.36
Fe (e)	4383.55	4383.3505	-11.70 ± 2.36
Hβ (F)	4861.34	4861.1257	-11.27 ± 2.36
Fe (c)	4957.61	4957.3006	-16.76 ± 2.36
Mg (b4)	5167.33	5167.1425	-8.93 ± 2.36
Fe (b3)	5168.91	5168.6520	-13.02 ± 2.36
Mg (b2)	5172.70	5172.4463	-12.76 ± 2.36
Mg (b1)	5183.62	5183.4332	-8.86 ± 2.36

were determined by calculating the standard deviation between the measured velocity and the accepted value for a given observation for each observing run.

For the data obtained in June 2017, we see that the measured radial velocity of HD 177409 ranges from -13.12 km s^{-1} to $+37.55 \text{ km s}^{-1}$. We note that the latter value was obtained on the night of 2017-06-13. We deduced from Figure 6 that it was likely that the slit was moved between the target exposure and the comparison lamp and we exclude that night from our current analysis. Using the data from 09–12 June 2017, we find that the average measured radial velocity for HD 177409 is $-5.51 \pm 8.73 \text{ km s}^{-1}$. Upon examination of the left panel of Fig. 10 we see no obvious signs of systematic errors in our measurement of the radial velocity of HD 177409 and the mean radial velocity is consistent within the errors of the published value.

From the data obtained in June 2018 with both the $0''.45$ and $1''$ slits, we see that the measured radial velocity ranges from -16.20 km s^{-1} to -0.22 km s^{-1} with an average value of $-8.83 \pm 5.73 \text{ km s}^{-1}$. This is in very good agreement with the radial velocity of HD 177409 from the literature. If we individually consider the data obtained with the $0''.45$ and $1''$ slits, we find that the average measured radial velocity of HD 177409 is $-12.80 \pm 5.49 \text{ km s}^{-1}$ and $-5.52 \pm 6.47 \text{ km s}^{-1}$, respectively. Both slits are measuring the accepted radial velocity of HD 177409 within the errors.

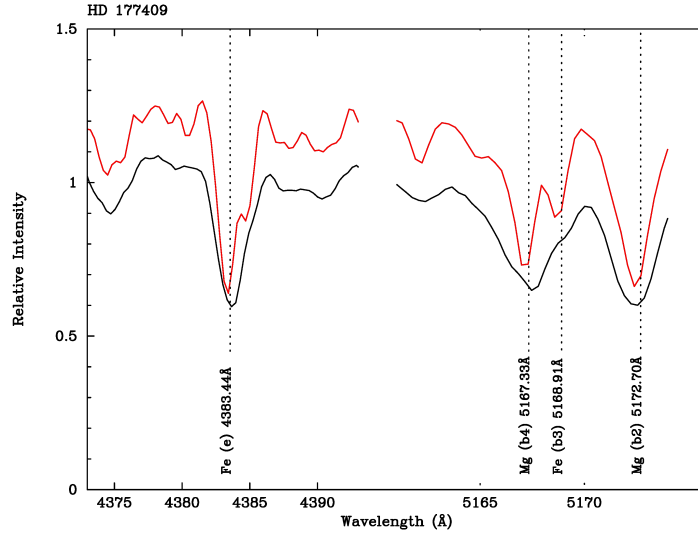


Figure 9. Resolution difference between 0.45'' slit (red) and 1'' slit (black). The 0.45'' slit better resolves absorption features allowing for a more accurate measurement of the radial velocity. Given the rest wavelengths of the lines, we can see that the 0.45'' slit measures the known blue-shift of the target. Because of blending, the wider 1'' slit gives a less accurate radial velocity for the object.

Table 4. Calculated Radial Velocity for HD 177409 by Line Identification

Object	Obs. Date	Obs. Time	Slit Width	V_{Helio}
	(UT)	(UT)	(arcsec)	(km s ⁻¹)
HD 177409	2017-06-09	09:34:30	1''	-13.12 ± 8.73
HD 177409	2017-06-10	08:20:51	1''	0.14 ± 8.73
HD 177409	2017-06-11	08:38:56	1''	3.73 ± 8.73
HD 177409	2017-06-12	09:00:43	1''	-12.81 ± 8.73
HD 177409	2017-06-13	10:29:31	1''	37.55 ± 8.73
HD 177409	2018-06-26	01:12:08	1''	-3.12 ± 5.73
HD 177409	2018-06-26	01:15:04	1''	-5.78 ± 5.73
HD 177409	2018-06-26	01:29:38	0.45''	-11.82 ± 5.73
HD 177409	2018-06-26	01:40:04	0.45''	-16.20 ± 5.73
HD 177409	2018-06-26	03:25:26	0.45''	-6.69 ± 5.73
HD 177409	2018-06-26	03:37:28	1''	-12.12 ± 5.73
HD 177409	2018-06-26	03:41:19	1''	-10.86 ± 5.73
HD 177409	2018-06-26	05:33:31	1''	-1.01 ± 5.73
HD 177409	2018-06-26	05:37:27	1''	-0.22 ± 5.73
HD 177409	2018-06-26	05:45:08	0.45''	-14.20 ± 5.73
HD 177409	2018-06-26	05:50:54	0.45''	-15.09 ± 5.73

We note that there may be a shift toward more negative velocities during each observation sequence. That is, the measured radial velocities are greater at the start of an observation sequence and then become more negative as the observations progress. We are cautious to over-interpret this. If real, it could be the result of changing between slits and re-acquiring the target. A more extensive investigation will be needed to confirm this. In any case, we recommend that radial velocity observers use the same slit over the course of a night.

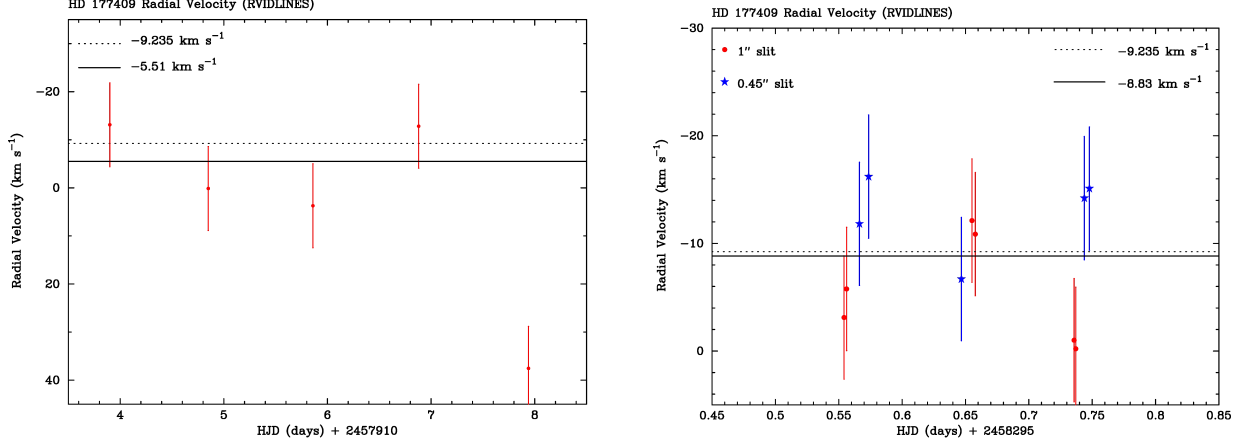


Figure 10. *Left:* Measured radial velocities of HD 177409 from observations obtained in June 2017 using the 1'' slit over five nights using the IRAF task `rvidlines`. The accepted radial velocity (-9.235 km s^{-1}) is plotted as a dotted line. The average velocity of the first four nights of observations (-5.51 km s^{-1}) is plotted as a solid line. The last night (UT 2017-06-13) was omitted from analysis because it is suspected that an optical element of the spectrograph was moved between the target exposure and the comparison lamp exposure, resulting in an erroneous wavelength solution as mentioned in §5 and shown in Figure 6. *Right:* Measured radial velocities of HD 177409 from observations obtained in June 2018 using the 1'' slit (red) and the 0.45'' slit (blue) using the IRAF task `rvidlines`. The accepted radial velocity is plotted as a dotted line and the average value of the measurements (-8.83 km s^{-1}) is plotted as a solid line.

6.3. Cross-Correlate Observed Spectrum with a Template to Calculate the Radial Velocity (Method 2)

Instead of manually identifying individual absorption features in the target spectra to determine a radial velocity, it is also possible to use cross-correlation techniques to determine the radial velocity. In this method, the object spectrum is cross-correlated against a template to determine the relative shift of the object to the template. This can be done in IRAF using the `fxcor` task. Before using the IRAF `fxcor` task, the observer will need to prepare both the data and the spectral templates that are being used. Before preparing the spectral template, the observer should first make sure that the spectral data have been prepared as we discussed in §6.1.

Before performing the cross-correlation, the spectral template data should be processed. One can choose between using synthetic template libraries or empirical template libraries. Both types of spectral templates have their advantages and drawbacks. For our purposes, we use the empirical spectral templates compiled by Kesseli et al. (2017, ApJS, 230, 2) that cover a range of spectral classes, luminosity classes and metallicities using SDSS BOSS spectra³. The spectral templates for the targets will also need to be continuum normalized as described in §6.1.4.

Once the spectral templates for the targets were obtained, we found it useful to update the template FITS header keywords to have the same values as the object spectra. The FITS header keywords that we found to be important were:

- OBSERVAT
- RA
- DEC
- DATE-OBS, and
- EXPTIME.

To update the template FITS header keywords, we used the WCSTools⁴ task `gethead` to obtain the values of the keywords from the target spectra. For example,

```
> gethead OBJECT OBSERVAT RA DEC DATE-OBS EXPTIME cdrvstd_045.0020.fits
```

returns the following:

³ <https://zenodo.org/record/321394#.W4nhqS3MxhE>

⁴ <http://tdc-www.harvard.edu/wcstools/>

> HD177409 soar 19:09:55.5940 -68:17:53.8100 2018-06-26T01:29:38.706 600.000000.

The keyword values for the target observations can then added to the FITS headers of the spectral templates using the IRAF task `hedit` or the WCSTools task `sethead`. We note that one needs to have same number of template spectra as your target spectra. For example, in Table 1 we have 16 spectra of one object for which we want to obtain radial velocity measurements. Therefore, we need 16 template spectra for the object that correspond to the different dates and times of the target observations.

After the spectral templates were obtained, continuum normalized, and the FITS header keywords were added or modified, we were able to use the IRAF `fxcor` task to perform the cross-correlation. The IRAF documentation for `fxcor` is extensive and it is beyond the scope of this document to describe all of the possible options. During our analysis of the spectra of the radial velocity standard star, HD 177409, we found that the most important parameters for the `fxcor` task were the rebinning, the object sample regions, and the template sample regions, *rebin*, *osample*, and *rsample*, respectively.

We set the *rebin* parameter in `fxcor` so that the cross-correlation would use the larger dispersion value between the target and the template. Given our success in identifying individual absorption features in the stellar spectra as described in §6.2, we set regions in the object and template spectra corresponding to 40\AA centered on $H\gamma$ (G'), $H\beta$ (F), and the Mg (b4), Fe (b3), Mg (b2), and Mg (b1) Fraunhofer lines. As shown in Figure 11, using a 40\AA sample region around the features of interest results in a systematic offset between the accepted and measured values of the radial velocity by $\sim 7\text{ km s}^{-1}$.

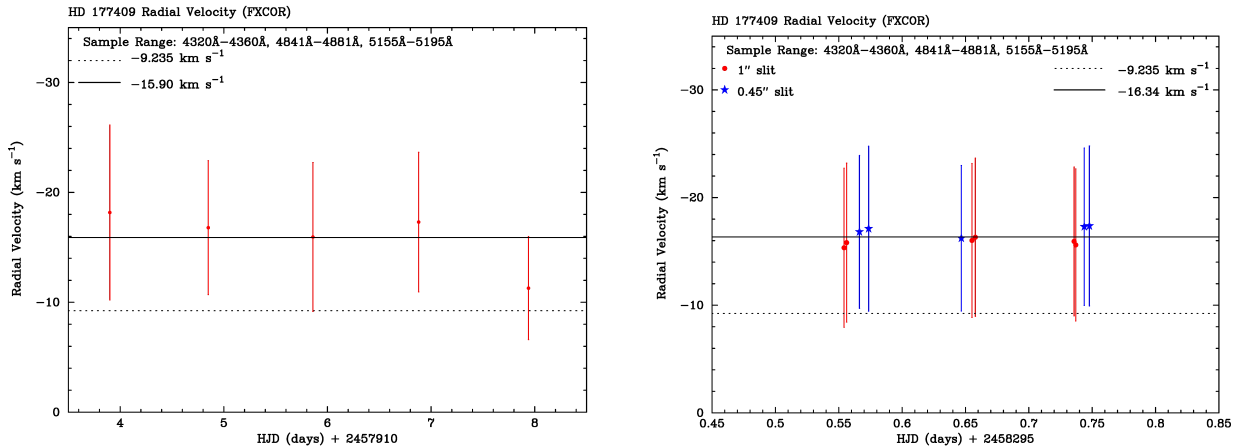


Figure 11. *Left:* Measured radial velocities using `fxcor` of HD 177409 from observations obtained in June 2017 using the $1''$ slit over five nights using 40\AA sample regions centered on $H\gamma$, $H\beta$, and the Fe and Mg lines at $\approx 5170\text{\AA}$. The accepted radial velocity (-9.235 km s^{-1}) is plotted as a dotted line. The average radial of the five nights (-15.90 km s^{-1}) is plotted as a solid line. *Right:* Measured radial velocities of HD 177409 using `fxcor` from observations obtained during one night in June 2018 using the $0.45''$ and the $1''$ slits and the same sampling regions as given above. The accepted radial velocity (-9.235 km s^{-1}) is plotted as a dotted line. The average radial velocity of the night (-16.34 km s^{-1}) is plotted as a solid line.

This systematic offset of $\sim 7\text{ km s}^{-1}$ between the accepted and measured radial velocity of HD 177409 using the cross-correlation method was surprising because the line identification method gave more accurate results. To investigate this, we changed the sample regions of the data and the template for the cross-correlation to 20\AA centered on $H\gamma$ and $H\beta$, and 30\AA centered on Mg and Fe lines at $\sim 5170\text{\AA}$. We present these results in Figure 12.

Thus, if one is using the cross-correlation task `fxcor` in IRAF it is important to set the sampling regions.

7. SUMMARY

- We have obtained spectra and calibration data for the radial velocity standard star, HD 177409, from the SOAR data archive and from scheduled engineering time.
- We have reduced these data using standard IRAF tasks.

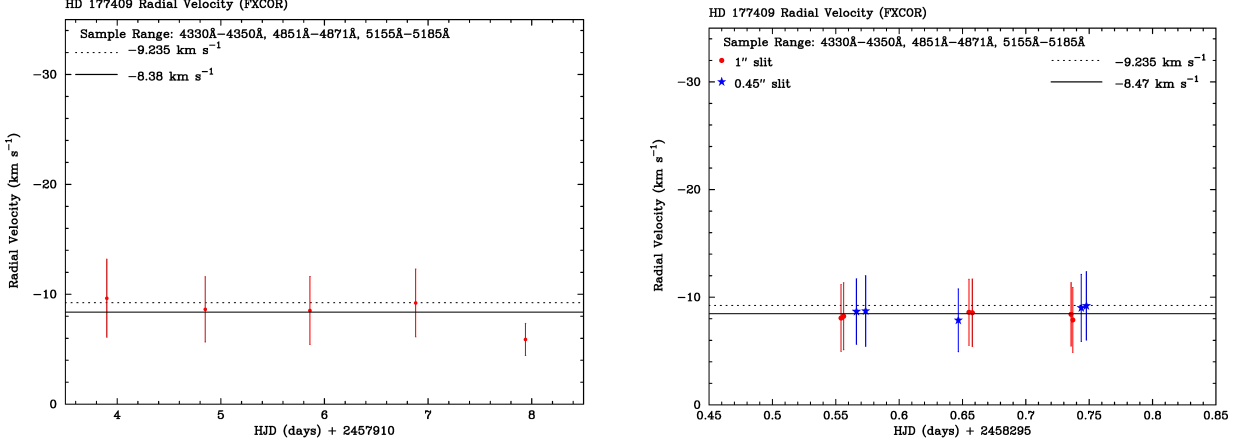


Figure 12. *Left:* Measured radial velocities using `fxcor` of HD 177409 from observations obtained in June 2017 using the 1'' slit over five nights using a 20Å sample region centered on H γ , H β , and a 30Å sample region around the Fe and Mg lines at $\approx 5170\text{\AA}$. The accepted radial velocity (-9.235 km s^{-1}) is plotted as a dotted line. The average radial of the five nights (-8.38 km s^{-1}) is plotted as a solid line. *Right:* Measured radial velocities of HD 177409 using `fxcor` from observations obtained during one night in June 2018 using the 0.45'' and the 1'' slits and the same sampling regions as given above. The accepted radial velocity (-9.235 km s^{-1}) is plotted as a dotted line. The average radial velocity of the night (-8.47 km s^{-1}) is plotted as a solid line.

- We have seen (i.e., Figure 6) that the dispersion solution for data obtained by Goodman is stable over time on scales of minutes, hours, days, and years as long as an observer follows the procedures outlined in §2.
- We have determined the observed radial velocity of HD 177409 using the individual line identification and cross-correlation techniques.
- Using the line identification method, we obtain accurate measurements of the radial velocity of HD 177409 with $7 \pm 2\text{ km s}^{-1}$ errors using the 1200 l mm^{-1} grism and the 0.45'' and 1'' slits.
- Using the cross-correlation method, we obtain accurate measurements of the radial velocity of HD 177409 with $3 \pm 1\text{ km s}^{-1}$ errors using the 1200 l mm^{-1} grism and the 0.45'' and 1'' slits after selecting appropriate sampling regions.
- A certain amount of trial and error seems to be necessary to measure an accurate radial velocity with Goodman regardless of methodology. The implication of this is that your radial velocity standards should be as close in spectral type as practical to your targets, otherwise they do not provide a full check on your results.

Facilities: SOAR (Goodman)

Software: IRAF (<http://iraf.noao.edu/>), WCSTools (<http://tdc-www.harvard.edu/wcstools/>)