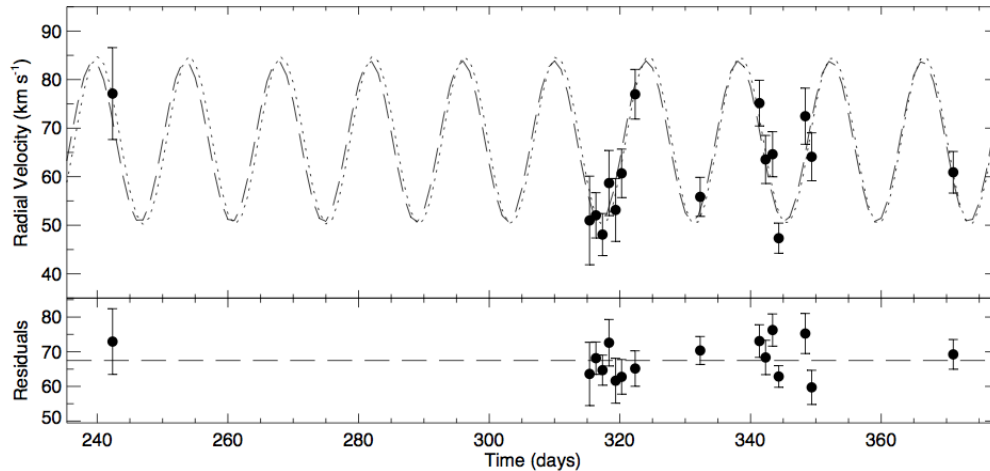


## Measuring Radial Velocities

With the proper setup and calibration frames, the Goodman spectrograph can measure radial velocities accurate to 5 km/s. To illustrate this, we show in Figure 1 the radial velocity curve for CS 1246 ( $V=14.6$  mag), a binary star system in which the visible companion orbits the system barycenter with a velocity of 16.6 km/s. The velocity curve, which has a mean noise level of 4.9 km/s, was created from data taken with the Goodman spectrograph.



**Figure 1** Radial velocities of a hot subdwarf star in a binary (measured with SOAR/Goodman: 2100 1/mm grating, 0.46" slit, Fe-lamp for wavelength calibration). The dashed line shows the predicted RV variation, which has a period of 14.1 days and semi-amplitude of 16.6 km/s. The mean noise level is 4.9 km/s.

The observing procedure we used to achieve the above results is summarized as follows:

### Summary of Observing Strategy

- 1) Align target on slit while guiding on field
- 2) Take comparison lamp spectra (immediately before object spectra)
- 3) Take object spectra (for no more than 30 minutes)
- 4) Take comparison lamp spectra (immediately after object spectra)
- 5) Repeat 1-4 for radial velocity standard star

*(see step-by-step detailed procedure on next page)*

In this document we present full details of the observing (Part 1) and reduction/analysis (Part 2) strategies used to create Figure 1.

## Part 1: *Observing Strategy*

### 1. Align the target on the slit and prepare spectrograph for spectroscopy

Following the instructions presented in the “[Taking a Spectrum](#)” document, we aligned the target on the slit and configured the spectrograph for spectroscopy. A quick review of this procedure follows:

- a) image the field and start guiding
- b) measure target position
- c) load a slit mask
- d) image the slit mask
- e) measure slit position
- f) move the star on the slit
- g) image the slit, check alignment (repeat above steps if not aligned properly)
- h) set to spectroscopic mode (set grating, camera/grating angles, ROI, etc.)

The spectroscopic setup we used is shown below:

#### *Spectroscopic Setup*

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<b>Grating:</b>	2100 1/mm	<b>ROI:</b>	Spectroscopic 1x2
<b>Slit:</b>	0.46”	<b>Readout Mode:</b>	200 kHz, ATTN 0
<b>Camera Angle:</b>	51 deg		
<b>Grating Angle:</b>	25.5 deg		

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### 2. Ask the operators to note the current telescope coordinates

With the target aligned on the slit, we asked the operators to write down the current telescope coordinates as the ones to return to if guiding was interrupted. This allows us to resume taking target spectra immediately after comparison lamp spectra without re-aligning the target on the slit.

### 3. Take comparison lamp spectra

After having the operators insert the comparison lamp mirror and turn on the “Iron” lamp (FeAr), we took four spectra of the lamp with integration times of 30 seconds using the same instrument configuration shown above. The Fe lamp was chosen because its emission lines (1) have a reasonable signal-to-noise ratio after 30-s of integration, (2) are mostly un-blended, and (3) cover the full wavelength range in our setup. We took multiple exposures to ensure a high signal-to-noise ratio in the combined calibration spectrum and that cosmic rays did not interfere with our ability to wavelength-calibrate the spectra.

#### **4. Return to guiding on the target**

Once we were satisfied with the first group of calibration spectra, we asked the operators to store the comparison lamp mirror, turn off the comparison lamp, and return to guiding on the target.

#### **5. Take spectra of the target (< 30 minutes worth)**

Without re-imaging the field, we took spectra of our target using the same instrument configuration described above. Although the telescope typically returns to same position after resuming guiding on the field, we took a quick “test” spectrum with a short integration time (~30s) to make sure the star was still on the slit before starting a series of spectra with longer exposure times. In those rare cases in which the star was *not* aligned to the slit, we started over at Step 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 one-time 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. In practice the problem never occurred in any of the data taken for CS1246.

#### **6. Take comparison lamp spectra**

We asked the operators to insert the comparison lamp mirror and turn on the Iron lamp and proceed to take four more 30-second exposures of the calibration lamp spectrum without moving any component of the spectrograph.

#### **7. Repeat Steps 1-6 for a radial velocity standard**

In addition to observing our target, we took spectra of a radial velocity standard star in the same setup used for the object spectra in order to calibrate the radial velocity zero-point. We followed the same procedure outlined above for the object spectrum.

## Part 2: *Reduction & Analysis Procedures*

Below we present the general procedure used to make the RV measurements shown in Figure 1.

### 1. Prepare the FITS files for wavelength-calibration

Using IRAF, we prepared the spectral images for wavelength calibration:

- trimmed pre-scan, over-scan, non-spectral regions out of all frames using *ccdproc*
- used *zerocombine* to make master bias frame
- bias-subtracted all flat frames using *ccdproc*
- made master flat using *flatcombine*
- bias-subtracted and flat-fielded object spectra using *ccdproc*
- made one master target spectral image by averaging target spectra using *imcombine*
- made two master comparison lamp spectral images by averaging consecutively-taken spectra using *imcombine*

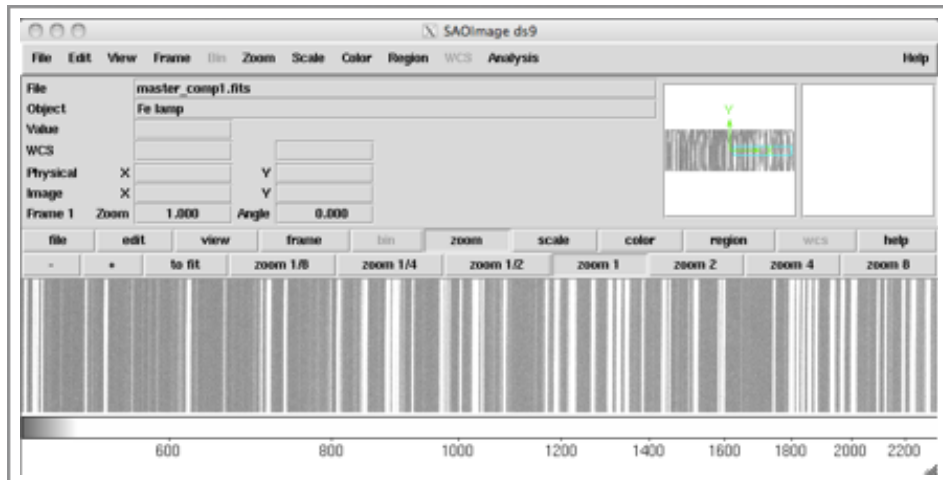
This process left us with 3 fully-reduced spectral images:

*1 master target spectral image*

*2 master comparison lamp spectral images (one taken before the target spectra, one after)*

### 2. Inspect the stability of comparison lamp lines

To investigate changes in the wavelength solution during our target observations, we opened the master comparison lamp spectra taken before and after target spectra in *ds9* and blinked the frames back-and-forth. Zooming in on various spectral features, we saw no significant shifts in the emission line positions and decided to combine the spectral frames into a single master comparison lamp spectrum to be used for the wavelength calibration.

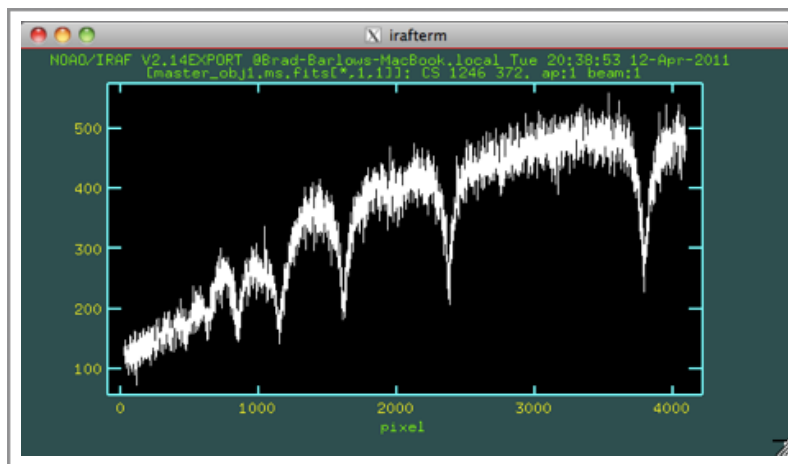


### 3. Combine the 'before' and 'after' comparison lamp spectra

Using the *imcombine* routine in IRAF, we averaged together the comparison lamp spectral images taken immediately before and after the object spectra into a single master spectrum.

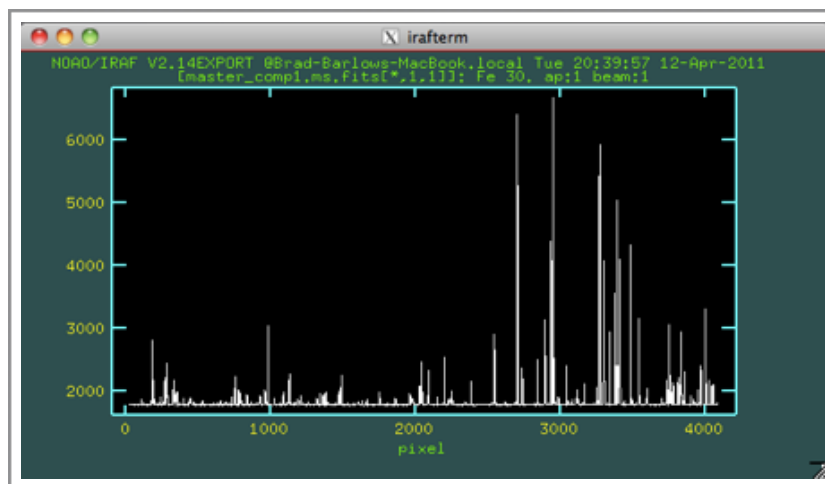
### 4. Extract one-dimensional spectrum of the target

We extracted a one-dimensional spectrum of the master object frame using the *apall* routine and inspected the result using *splot*.



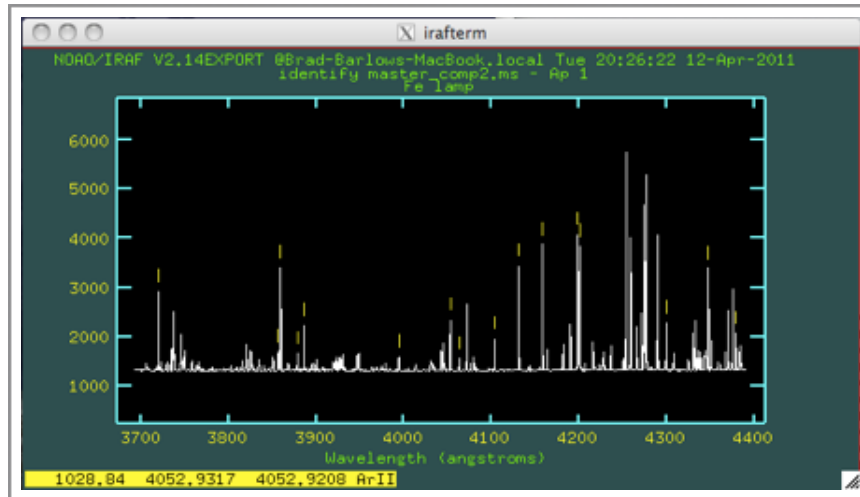
### 5. Extract one-dimensional spectrum of the calibration lamp

Applying the same aperture trace used for the target (in *apall*: *referen=target\_name.fits*, *fittrac=no*, *interac=no*), we extracted a one-dimensional spectrum of the comparison lamp and inspected the result.

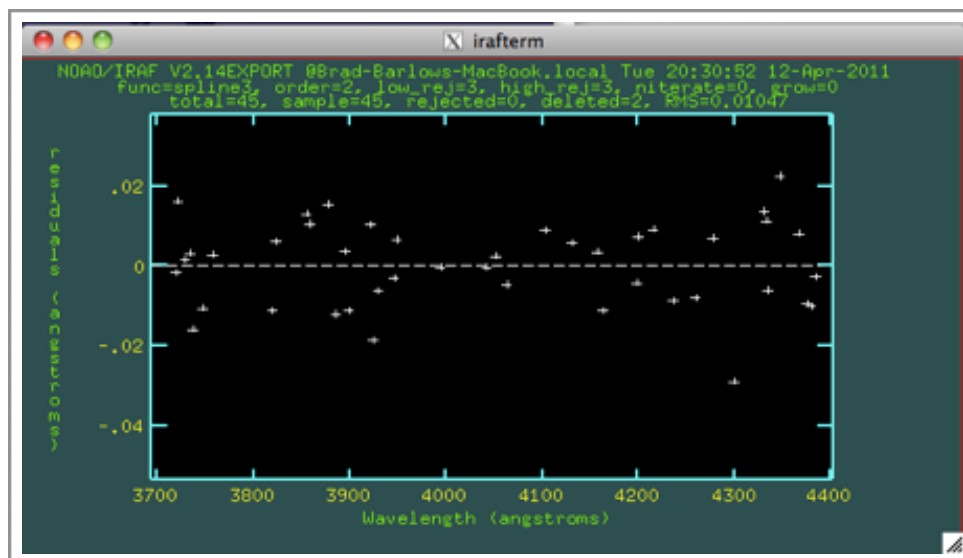


## 6. Identify lines in the calibration lamp spectrum

First, we downloaded an Iron-Argon line list from the NOAO *Spectral Atlas* (<http://www.noao.edu/kpno/specatlas/>). We used the *identify* routine in IRAF to enter the wavelengths for approximately 15 lines by hand ('m' key), using the plot from the *Spectral Atlas* as a guide.



We then had *identify* locate other features from our line list by hitting 'l' and fit a second-order cubic spline to the wavelength solution using the 'f' key. The RMS scatter was usually around 0.01 Angstroms.

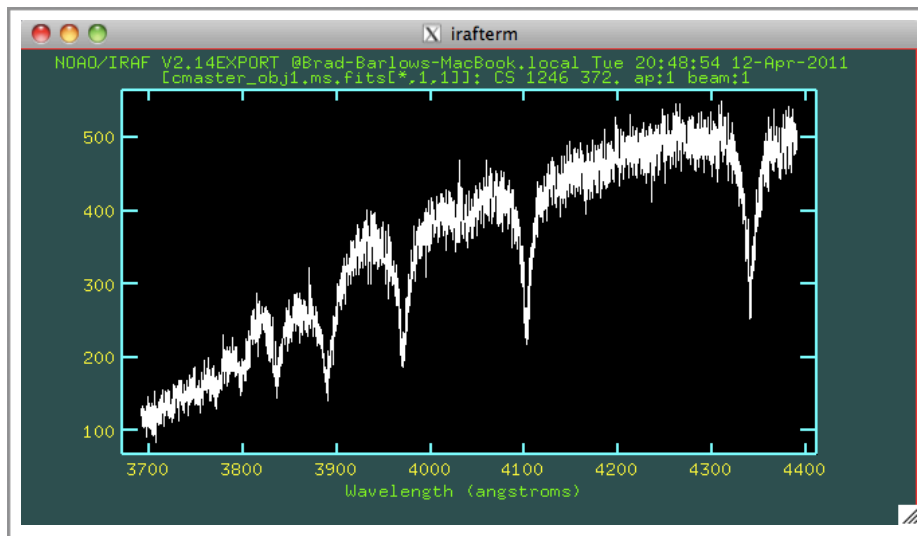


## 7. Apply wavelength solution to object spectrum

We used the *refspec* and *dispcor* routines to apply the wavelength solution to the object spectrum.

### *dispcor* output:

```
onedspec> dispcor
List of input spectra (master_obj2.ms.fits):
List of output spectra (cmaster_obj2.ms.fits):
master_obj2.ms.fits: REFSPEC1 = 'master_comp2.ms 1.'
cmaster_obj2.ms.fits: ap = 1, w1 = 3691.954, w2 = 4391.048, dw =
0.171557, nw = 4076
```



## 8. Measure radial velocity in object spectrum

Using the MPFIT routine in IDL, which employs the Levenberg-Marquardt method, we fit the sum of a Gaussian and Lorentzian to the individual hydrogen Balmer line profiles in the spectrum and used the best-fit centroid values to compute velocity shifts from rest-frame values. Balmer lines beyond H9 were ignored since the low signal-to-noise ratio in this part of the spectrum resulted in inconsistent fits. We estimated the velocity error in each master spectrum using the standard deviation of the individual line-profile measurements.

## 9. Repeat steps 1-8 for radial velocity standard spectrum

We applied the same reduction and analysis procedure to a radial velocity standard star spectrum to check our zero-point velocity. Our RV measurements agreed with the published values to within the error bars ( $\sim 3$  km/s), and consequently we made no zero-point adjustments to the CS 1246 RV values.