In this lab, we’ll carry out the remaining steps needed to generate a wavelength-calibrated stellar spectrum.

In class, you received a picture of the thorium-argon spectrum for the spectral region assigned to you to process, with three lines identified. If you have not done so already, process both the comp exposure taken before your star and the one taken after. See the instructions for Lab 3 for details. Check for cosmic rays by comparing the two comp images and ignore features that are narrower than the normal FWHM of 4.3 pixels. Cosmic rays can mimic comparison lines and confuse your line identifications.

1 Determining the Wavelength Calibration

In order to make a fit of the line wavelengths to the pixel numbers of the lines, run the task identify in the package onedspec. Here are the important parameters for this task.

```
PACKAGE = onedspec
TASK = identify
images = comp11b Images containing features to be identified

... 
(databas= database) Database in which to record feature data
(coordli= linelists$thar.dat) User coordinate list

... 
(ftype = emission) Feature type
(fwidth = 4.) Feature width in pixels
(cradius= 5.) Centering radius in pixels

... 
(functio= chebyshev) Coordinate function
(order = 4) Order of coordinate function
(sample = *) Coordinate sample regions

... 
(autowri= no) Automatically write to database

... 
```
If you find you can’t satisfactorily identify at least 6 lines, change the function to a lower-order polynomial such as a chebyshev polynomial of order 3.

To start with identify, place the cursor on the identified lines and use the m key to mark each one. Type the given wavelength when prompted. Now use the 1 (lowercase letter “L”) key; the program will provide a list of proposed identifications matching the Th-Ar line list that is on the computer. Inspect each one and delete features that are likely to be caused by noise fluctuations or by the scattered light near the middle of the spectrum. Make a new fit with f and inspect the residuals. Delete extreme outliers and type f again. Be cautious about deleting outliers, though. When you are satisfied, type q to quit the curve fitting routine and q again to quit the task. You should be able to bring the rms residual down to below 0.1 Å. Write the feature information to the database, and write down the value of the rms on paper; it will not be saved to the database.

When you have processed both comparison spectra with identify, your database directory will contain two text files whose names start with the letters id, one for each of the two comp images. Display them to your screen with a task such as page and compare the listed pixel positions for the comparison lines. In your Results section, discuss the difference between the pixel locations between the two images, in comparison with the rms values for the comparison line fit, and in the context of your radial velocity measurement accuracy (see below). Is it a good thing that we bracketed the stellar observations between two comp spectra?

2 Analysis of the Th-Ar Spectrum

In one of your extracted comp spectra, make Gaussian fits to all the apparently single comparison lines by means of the k key in splot. Instructions for using the k key will be given in class. From the average full width at half maximum of the fitted Gaussians, determine the resolution and the resolving power (λ/Δλ) of the échelle spectrograph. Include one or more sample Gaussian fits in your report. Does the Gaussian appear to be a good approximation to the instrument profile of the spectrograph?

3 Calibrating the Stellar Spectrum

Now apply to the stellar spectrum the wavelength calibration that you have just derived. The first step is to append the keywords REFSPEC1 (the name of the first comp spectrum) and REFSPEC2 (the name of the second comp spectrum) to the image header of the stellar spectrum that you wish to calibrate. To do so, use the task hedit with add=yes, update=yes. The second step is to run the task dispcor with the stellar spectrum as the input spectrum. The only other important parameters are lineari= yes and flux = no (Conserve flux?). The latter controls how the pixel values are treated when the x axis is converted from flux to wavelength. Pixel boundaries change, and interpolation or grouping of pixel values may occur. By setting flux = no, you tell the task to form averages of pixel values rather than sums.

Compare your spectrum with the version in the Ritter archive of reduced data: /mnt/vol01/ritter/Reduced/archive. Caution: displaying the directory of the entire archive is not recommended; it is very large. Copy the reduced spectrum to your account and display it with splot. Since the reduced spectrum includes all 9 apertures, splot will ask you to choose one.
4 The Heliocentric Correction

Now you are ready to convert the spectrum to the heliocentric rest frame. Steps:

- Load the package `astutil`. In its parameter list (`epar astutil`), check that the first parameter is set to `obspars`. (I forgot to do this in class.)

- Set the parameters for the task `observatory` as follows.

  ```
  command = "set" Command (set|list|images)
  obsid = "obspars" Observatory to set, list, or image default
  images = List of images
  override = "obspars" Observatory identification
  (verbose = yes) Verbose output?
  (observatory = "obspars") Observatory identification
  (name = "Ritter") Observatory name
  (longitude = 83.61) Observatory longitude (degrees)
  (latitude = 41.65) Observatory latitude (degrees)
  (altitude = 100.) Observatory altitude (meters)
  (timezone = 5.) Observatory time zone
  (mode = "ql")
  ```

- Edit the header of your stellar image, adding the keyword `UT`. Its value should equal the time of mid-exposure, halfway between the values of the keywords `TIME-BEG` and `TIME-END`.

- Run `rvcorrect` with the second parameter (`images`) set to the name of the stellar spectrum. The task will output values for `HJD` and `VHELIO`. If you set the task parameter `imupdate=yes`, the keywords `HJD` and `VHELIO` will be added to the image header.

- The actual conversion of the wavelength scale of the stellar spectrum can now be done. The command line is `dopcor spectrum1 spectrum2 -vhelio isvel+` where `spectrum1` is the existing spectrum and `spectrum2` is the corrected spectrum that you want to create.

5 Continuum Normalization

In the corrected spectrum, select line-free regions and fit a linear continuum to them with the task `continuum`. Because you are working on a cool star whose spectrum is crowded with absorption lines, this step requires judgement. Find the three to five highest points in the spectrum, and select them as sample ranges. Fluctuations of the data within those ranges should be due to photon noise only, and your fitted function should run through the averages of those points. When satisfied with the fit, save the graphics screen with `.write`, including a plot of the whole spectrum and zoomed-in plots of the parts that you fitted. You can save several plots to the same file. Include in your report the plot of the whole spectrum and any interesting zoomed-in plots.

6 Line Identifications

In `/mnt/vol01/ndm/iraf/course/F2005/linelists-echelle1.pdf` is a list of lines from the CD-ROM version of Visible and Near Infrared Atlas of the Arcturus Spectrum, 3727-9300 Å by
Kenneth Hinkle, Lloyd Wallace, Jeff Valenti, and Dianne Harmer (San Francisco: Astronomical Society of the Pacific, 2000). Arcturus (α Boötis, K1IIIb) is similar in spectral type to the star you are working on, and its spectrum should include similar lines, although the strengths of individual lines may differ because of slight differences in temperature, luminosity, and chemical composition. The radial velocity of Arcturus is listed\(^1\) as \(-5 \text{ km s}^{-1}\) but may be slightly variable.

In the directory `/mnt/vol01/ndm/iraf/course/F2005` I have placed three sections of the Arcturus spectrum itself, from the same reference, called `arcturus5.fits`, `arcturus7.fits`, and `arcturus9.fits`. Overplot the proper one with your spectrum to see how they match up. In the Arcturus spectrum, water vapor lines from the Earth’s atmosphere have been artificially removed, but locations where the procedure did not work well have been replaced by data values of \(-1\).

The resolution of the equipment with which the Arcturus spectrum was obtained is significantly higher than the resolution of our spectrograph. In comparing the spectra, show an example of a feature where the lower resolution of our instrument makes a significant difference.

Measure the wavelengths of the 10 or so strongest, apparently single, or “unblended,” lines in the Arcturus spectrum corresponding to your spectrum, and identify these lines by comparison with the line list. Then identify the same lines in your own spectrum. Present a line list with your report, and show a graph of your spectrum with the identified lines marked. You can label a graph in `splot` (or any graphics screen in IRAF) by means of the `T` key.

7 Measuring Radial Velocities and Equivalent Widths

With the `e` key in `splot`, measure the wavelength and equivalent width, in the heliocentric corrected spectrum, of each line that you identify. From the wavelength, calculate the star’s radial velocity by means of the Doppler formula,

\[
\frac{\lambda - \lambda_0}{\lambda_0} = \frac{v_r}{c},
\]

where \(\lambda\) is the measured wavelength of a line and \(\lambda_0\) is the laboratory wavelength, \(v_r\) is the radial velocity, and \(c\) is the speed of light. Average the values together to calculate the radial velocity of the star, and calculate the standard deviation of the values to obtain an error estimate for the radial velocity. Such an estimate is sometimes called the *internal error* of the measurement, because it does not include instrumental effects that could erroneously shift all the lines together. Compare your mean and standard deviation with the published radial velocity of \(\gamma\) Aql, \(-2.1 \text{ km s}^{-1}\) (assume negligible error; according to SIMBAD, this value is the average of 102 measurements).

8 Your Report

Everything in this section of the instructions for Lab 1 also applies to this lab. Be sure to document each step fully with captioned graphs and tables, as needed. Present and discuss graphs of your results.