Spectroscopy

1 Introduction

In this lab, you will analyze the spectrum of an interesting source to determine its radial velocity (or redshift), and other information about it.

We do not have access to a spectrograph at the moment, so we'll use some data that were taken for the last offering of A61. I (John Thorstensen) and undergraduate Alexandros Zervos obtained these in 2013 October, using the Modular Spectrograph on the MDM 1.3 meter telescope. The data I'm giving you are already bias-subtracted and flatfielded – these steps are pretty similar to what you've already seen in previous labs – so you can concentrate on the spectroscopy.

2 The Targets

The previous Astronomy 61 class selected several targets for observation. The bias-subtracted, flatfielded images for these are in the data packet.

In addition, there are spectra of comparison lamps, which are little lamps in the telescope filled with various gases that emit spectral lines when a current is passed through them. One exposure has mercury and neon lamps (HgNe); the other has xenon lamps. The reason for doing two exposures is that the HgNe lamps are much brighter than the Xe; HgNe gets a good exposure in 0.1 seconds, while the Xe exposure is 60 seconds long! Although Xe is weak, we do need to include it because there's a wide region of the spectrum in the blue where HgNe has no lines usable for calibration.

3 What's what?

Use the IRAF/Pyraf task *hselect* to figure out what image is what. Notice that the IMAGETYP keyword will be COMPARISON or OBJECT, which helps keep them straight. Looking toward your writeup (at the end) you can save time now by constructing your observing log summary.

4 Finding Chart

Just for practice, make a *finding chart* for the quasar, B0624+6907. Its J2000 RA and dec are 06:30:02.6s, +69:05:03. To make the finding chart, use ds9, find *Image servers* under *Analysis* – STScI is a good choice of server, and DSS2-red is a good survey to use, though any will do. Enter the coordinates in the search box using colons as shown. Be sure to label your chart, using the Region menu ("Shape" makes it possible to insert text). A well-labeled chart should have the coordinates, the name of the object, and an indication of the scale and direction of north and east;

for this last, you can use the *Compass* shape, which automatically points north and east because the image has world coordinates. Find your object using its coordinates; mark it with little lines. Finally, save your image under the File/Export menu; export it as a PNG file.

5 Analysis

Each member of the group must analyze the data individually. You may discuss your analysis with other members of the group. You'll have to analyze it with IRAF/Pyraf. To get to most of the tasks needed for this, you type /it noao, followed by *imred*, followed by *specred*.

Here's an outline of the steps required, with many details missing:

1. Orient yourself by looking at the images with ds9 (not part of IRAF). Wavelength runs vertically (the wavelength axis is Y), and the spatial direction is horizontal. Bluer happens to be toward the top. The vertical stripe is the object's spectrum. The bright horizontal lines are emission lines that fill the entire slit – consider where they might come from. Whatever they are, we'll need to subtract them away at some point, since they aren't part of the object's spectrum. Note that you can use *implot* in pyraf to view 'cuts' through the raw data. If you're looking at a row, typing 'c' plots the column that's under the cursor; if you're looking at a column, typing 'r' plots the row that's under the cursor.

2. Now comes the elaborate process of extracting a 1-d spectrum from the 2-d image. Do this first for the program objects, not the comparisons. Use *apall* for this. This has about a zillion parameters, some of which are not at all obvious, and most of which are not critical. It'll take a while to get the first spectrum properly extracted. A few pointers: Output format should be 'multispec'. Go ahead and set all the yes/no boxes to 'yes'. For default aperature parameters, -5 to $+5$ works well, and for default background use something like $-50 : -10 : 10 : 50$, to get a wide stripe on either side. The Extraction Parameters are important; subtract the "fit", Box car length must be 1, weights are 'variance', pfit is 'fit1d', detect and replace bad pixels is 'yes'. Saturation level is 60000 or so, readnoise is 8, and gain is 3. Once you run apall on a spectrum, you can examine your results using *splot*, which you'll use later. The multispec file has a suffix *.ms*, and contains four spectra stacked in one file; spectrum 1 is the optimally extracted spectrum, 2 is the same as 1 but without fancy extraction, 3 is the background that's been subtracted, and 4 is an estimate of the uncertainty in each pixel. You can switch between these in *splot* using ')' and '('.

3. Use imarith to add the HgNe and Xe 2-d images together. Extract a 1-d spectrum using apall (again), but now in the *onedspec* format. If you use one of your program object spectra for the reference and profile images, then apall will extract the 1-d comparison spectrum using the aperture you so laboriously defined for the star. This will make it so that the the wavelength calibration is for the same part of the chip that your data were taken with, which is just what you want.

4. The horizontal axis for your one-d spectra is in *pixels*, but you want it to be in *wavelength* λ. Now, the comparison lines all have very accurately known wavelengths, and by measuring

the center of the line you can find the exact (fractional) pixel number x at which the line is centered. This gives you a couple of dozen (x, λ) pairs. But you'd like to know the wavelength at *any* x along the spectrum. One way to do this would be to construct straight lines between adjacent the (x, λ) points; this wouldn't do badly, but we can do much better. by using a more sophisticated form of interpolation. We use the *identify* task to measure the line centers and derive a *polynomial fit* to the (x, λ) pairs. Once you have the polynomial, you can evaluate it at any x to give a very accurate λ. The task will want a list of known wavelengths; I've provided a little file *hgnexe* that gives a list of good lines, and a file *wavelengths.ps* that shows a 'cartoon' of the wavelengths of the lines. To operate *identify*: Use the '?' key to explain what different keys do; to start. Use 'm' to mark features and tell the program what the wavelengths are; that'll get you started. After that, 'l' (ell) will look for other lines. 'f' does a fit and shows you the residuals. When you're looking at the fit, typing ':o 5' (for example; 'colon oh 5') changes the order of the polynomial fit. Notice that the polynomial fits are called 'chebyshev' or 'legendre'. These are different sets of *orthogonal polynomials*, which are much more stable numerically than simple polynomials.

5. Once you're happy with your wavelength solution, use 'refspec' to tell the program objects which solution to use.

6. Finally, use 'dispcor' to create dispersion-corrected spectra.

7. Use *splot* to test your wavelength solution. Display the background spectrum subtracted from the spectrum (line 3). There should be a strong line present near 5577 Å. Expand the plot around this (by typing 'a' with the cursor on either side of the line). Measure the wavelength exactly by fitting a gaussian – 'k' at the base on either side of the line does this. Look up the actual wavelength on the NIST Atomic Spectral lines database at

   http://physics.nist.gov/PhysRefData/ASD/lines_form.html

   ... the spectrum is "O I" (neutral oxygen). You should be good within a few hundredths of an Å. If not, you may want to tune up the *identify* a bit and repeat the *dispcor*.

Once you have the spectra reduced to counts *versus* wavelength, you can do some analysis on them.

1. Identify the most prominent lines in each star spectrum (i.e., fing out what specie produces the line). Ignore the quasar spectrum for now.

2. Estimate the spectral classifications of the stars. For comparison, you may find Jacoby, Christian, and Hunter's article userful (its bibcode is 1984ApJS...56..257J). Notice that your spectra are not flux-calibrated, so the shape of the continuum are not physically meaningful; you have to do the classification on the basis of the presence and relative strengths of the absorption lines. After you've estimated this, look them up on SIMBAD; that should give more refined spectral classifications. How well did you do?

3. Find the radial velocities of the stars by measuring some of the most prominent lines, comparing to their rest wavelength, and using the Doppler formula. Of course, the data were taken from earth, which is a moving platform, so repeating this at different times of year would give different answers, because the earth's velocity changes direction as it goes around its orbit. To account for this, use JSkyCalc to compute a *barycentric correction* (just set up the observation in JSkyCalc, refresh the output, and read off the field toward the lower right). The barycentric correction is the velocity that would be observed by a fictitious observer who has the velocity of the barycenter, or center of mass of the solar system, which moves almost exactly in a straight line at a constant speed in accordance with the laws of mechanics. The barycenter is usually, but not always, inside the sun, the main effect being the influence of Jupiter, which perturbs the barycenter by about 12 m s^{-1}. As a final step, add the barycentric correction to your raw velocity, and check the result against the SIMBAD value (if any).

4. The quasar spectrum presents a more interesting challenge, because as Maarten Schmidt discovered back in the 1960s, these can have very large redshifts – redshifts large enough that their spectral lines can appear at wavelengths that are several times longer than the rest wavelength! Identify some lines in the spectrum of your quasar and measure its redshift, $z = (\lambda - \lambda_0)/\lambda_0$, where λ is the observed wavelength and λ_0 is the rest wavelength. A nice composite quasar spectrum can be found in VandenBerk et al., 2001, Astronomical Journal, 122, 549 – especially their Figure 6. The breadths and relative strengths of the lines should a big clue. When you get the lines right, the redshifts derived from the different individual lines should agree to less than 1 per cent. Once you have the redshift, convert it into a radial velocity by multiplying by c, and then use the Hubble relation

$$v = Hd$$

with $H = 72$ km s^{-1} Mpc^{-1} to estimate the distance in megaparsecs. With large redshifts, the concept of radial velocity gets sketchy – the redshift is due mostly to cosmic expansion, which isn't the same thing as ordinary speed – and several different defintions of 'distance' make sense, but this gives a rough indication of the distance.

6 Writing up the Lab

You can hand in your lab as a PDF if you like.

Lab reports will be due after the Sutherland trip. 18. A complete lab report will consist of the following:

1. **Purpose:** A brief statement describing the purpose of the lab.
2. **Finding chart:** Include your finding chart; this can be electronic.
3. **Observing:** Based upon the FITS headers, construct an observing log for all of the data you used (included calibration images) in this lab. Your observing log should have a similar format to what you have used previously in this course (file name; target name/type of observation; date and time of observation; airmass; exposure time.
4. **Analysis:** Describe how you obtained a calibrated one-dimensional spectra from the raw data and determined its radial velocity and its error.
5. **Results:** Give your answers to the various questions. Discuss concepts that you learned, and problems you encountered, in doing the lab.