Name:.....

Astro 101: Observational Astronomy

Fall 2009

Lab 2: Stellar Photometry and CCD Characterization

1 Observations

1.1 Objectives

During this lab you will use the Brackett optical imaging camera, or observe remotely with TMO. You will be observing a variable star chosen from the list in Table 1. These objects are pulsating variable stars that belong to a class called δ Scuti and have typical periods of one to a few hours. Your goal is to construct the star's light curve in B and V filters to study how the luminosity and temperature of this object changes as a function of its pulsation phase.

Observations will be performed in teams of two on Tuesday (September 29) or Thursday (October 1). We will designate team assignments and start times in class. Keep in mind that the TMO observers will have to arrive early, about 15 minutes prior to sunset to perform twilight flats (sunset is at ≈6:35 pm).[1] **Please read through this entire manual and complete all the necessary preparations** *before* **the start of the lab.**

1.2 Background

The targets for this lab belong to a class of pulsating variable stars named after a prototype object δ Scuti. Like Cepheids, their better known cousins, δ Scuti stars are periodic variables whose brightness and temperature change due to radial oscillations; the stars are hotter when they contract and colder when they expand. Figure 14.6 in Carrol & Ostlie shows that a region in the HR diagram where these objects are found corresponds to F and A stars ($1.5 - 2.5 M_\odot$) just evolving off the main sequence.

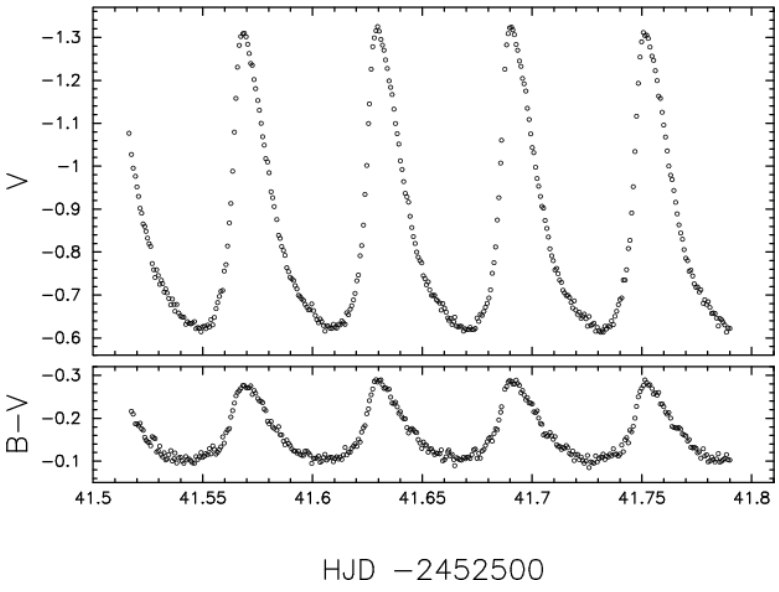

Figure 1: V-band light curve and B-V color index of CY Aqr (Fu & Sterken (2003)). V magnitude is given relative to a nearby comparison star, GSC 00567-01826. The pulsation period was found by Fu & Sterken (2003) to be 87.895287 ± 0.000009 min.

δ Scuti stars are interesting mostly as test cases for stellar evolution models, especially because their distances can be relatively accurately estimated from the period-luminosity relationship, analogous to that of the Cepheids. In figure 1, the light curve of one of your potential targets, CY Aqr, is shown. It presents an excellent differential photometry target since it is very bright, with $V \sim 11$ mag, and shows large amplitude (~ 0.7 mag) variability with detectable color changes between different pulsation phases. Also, its pulsation period of ~ 88 minutes is short enough to be covered during one observing period.

[1] Any time you plan to observe, you should check twilight times online (http://www.wunderground.com).

1.3 Pre-Lab Preparation

1.3.1 Target Selection

Choose a target from Table 1 that will be accessible during your planned observing slot. If you are planning on using TMO, recall that it cannot point more than an hour or so east of the meridian, so pick a target that is close to transiting (i.e. HA ¿ -1) at the time you start your observations. Other things to consider when you choose your target:

- What is the expected airmass of your target? Using the 'Airmass Calculator', check that your target's airmass stays below 2. (You can use Palomar as your observing site.)
- What is the period of variability? You will want to monitor your target for at least one full period, so the stars with periods longer that 2 hours are not ideal.
- How bright is the target? At the faint end, you will have larger flux uncertainties, so small variations will be harder to measure. If you are observing at Brackett, you should avoid the three dimmer targets.

Name	R.A. (2000)	Dec (2000)	Period (days)	Amplitude (V-mag)	V-mag
V802 Aql	18 58 55.	-03 01.2	0.1338	0.9	13.9
V484 Lyr	19 16 04.	+30 15.7	0.0756	0.5	15.9
XX Cyg	20 03 15.6	+58 57 16.5	0.1349	0.80	11.87
BP Peg	21 33 13.5	+22 44 24.3	0.1095	0.41	11.98
KZ Lac	22 18 46.5	+50 31 48.2	0.1166	0.6	14.9
CY Aqr	22 37 47.9	+01 32 03.8	0.0610	0.71	10.93
DY Peg	23 08 51.2	+17 12 56.0	0.0729	0.54	10.36

Table 1: Potential variable star targets taken from Rodriguez et al. (2000). The full revised catalog of δ Scuti stars can be queried at: http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=J/A+AS/144/469
More precise coordinates for the last five targets have been obtained from SIMBAD.

1.3.2 Standard Stars

You will want to observe 2 standard stars to perform differential photometry on your target. Ideally, the standards will be roughly the same brightness as your target and located in the same field. To choose good standards, download the field around your target into the DS9 and use the built-in DSS server (Analysis → Image Servers → ESO-DSS I/II) to examine the sky around it. Choose an image size equal to the FOV of your instrument. Start by confirming that the star in the center of your image is your target, i.e. that it has the right coordinates. Now overlay the HST Guide Star Catalog on your image. You can access this catalog in DS9 via: Analysis → Catalog → HST Guide Star Catalog. This will load and overlay the catalog on your current DS9 image and pop up the Catalog Tool window containing information about the stars in your field. Choose 2 stars of roughly the same brightness as your target. Record their coordinates and find them in the Catalog Tool table. Make sure the stars in the table are sorted by RA or Dec, to make the search easier. Note that the stellar coordinates in the Catalog Tool window are given in degrees, so to ease the comparison change WSC → Degrees in DS9. To double check whether or not you got the right star, click on the appropriate row in the Catalog Tool window and watch for a blinking circle in DS9.

If you cannot find suitable standards in your field, try looking at a slightly larger image, since you target does not have to be precisely in the center. In a pinch, one standard star would be sufficient, but if you are unable to find any, choose a different target.

Once your standards are chosen, record their GSC numbers; you will need them to look up their V and B magnitudes (there is only one magnitude in unknown band in the ESO version of GSC). To do that, go to

Astrophysical Resources → VisieR on the course webpage. Now type 'gsc' in the top search window. Now click on the button labeled 'I/305/out' which corresponds to GSC2.3.2 Catalogue. Type in the GSC number (e.g. GSC 02188-00551) of your comparison star under 'Target', and choose which parameters you want to view. At a minimum you will need RA Dec coordinates, GSC1 ID number, V photographic band magnitude, B Johnson band magnitude and their respective uncertainties. When you are done, click on 'Submit Query'. Find your star and record its magnitudes with uncertainties.

1.3.3 Finding Chart

The final preparation step is to construct a finding chart for the field that contains your target star and the two standards, ideally all located near the center of the field. You might want to choose an image size somewhat larger than the FOV of your instrument to help with telescope pointing. Some notes on making a good finding chart:

- Label your primary target (REGION → SHAPE → CIRCLE) and standard star targets.
- Label the central coordinates of the field (REGION → SHAPE → TEXT).
- Include a scale or at least note the FOV (REGION → SHAPE → RULER).
- Include a compass (REGION → SHAPE → COMPASS).
- Invert your greyscale so stars are black (COLOR → INVERT).
- Identify standard stars in your field (see §1.3.2).

To create the regions listed above, first select a region type, then click on your image. After it has been added, double click on the region to bring up a panel to change parameters like color, font, coordinate, units, etc. For the compass and ruler, the coordinate and length should be set to WCS. Save this chart and print a copy to bring with you. You will also want to include this finding chart in your lab report.

1.4 Procedure

If you are observing at Brackett, you will again be using The Sky to control the telescope and Maxim DL to control the camera. At TMO, the telescope control program is called ACE, but the data aquisition is done with Maxim DL as well. Your instructor will help you with any problems that might come up. Below, I will go over the main steps required to obtain your data.

1.4.1 Flats

At TMO, the first group of the night will arrive before sunset and take twilight flats that all groups from that night will use. Five flats per filter in the 10,000-40,000 count range should be sufficient. Make sure to start early enough not to allow time for the dome and CCD to cool down before twilight. The CCD likes to warm up itself up before cooling down (safety feature in the CCD design) and this takes about 15-20 minutes.

At Brackett you can do the same, however, you can also take the night flats as we did in Lab 1. In fact with the Moon getting close to full, the sky should be a lot brighter than last time, especially in the vicinity of the Moon.

1.4.2 Pointing and Focusing the Telescope

Start by pointing at a bright star and focusing the telescope. At TMO, the target star itself might be bright enough to use, at Brackett you might want to start with a brighter star. Since we will be doing aperture

photometry in an uncrowded field, perfect focus is not absolutely necessary, but you will get better signal-to-noise ratios with good focus. especially since we are observing near full moon phase, and the sky background is high!

The focus might be slightly different in the two filters. Pick a setting that works more or less for both, since you will not have time to reset the focus as you are switching back and forth between filters during the actual observations.

Once the telescope is focused, point to your target. It might be too dim to see in the eye-piece at Brackett (and of course an eye-piece is not an option at TMO), so take an exposure to make sure you are pointing in the correct direction. Compare the image with your finding chart and identify your target stars. Make any last minute adjustments to pointing to make sure that all of your targets (including standard stars) are as close to the center of the field as possible.

1.4.3 Photometry

You are now ready to take images of your target. First you need to decide what exposure time to use. In Maxim DL estimate the noise level by adding the fluctuation of the background and the sqrt of the peak count rate for the star, and compute *rough* S/N ratio for your target using equation

$$\frac{\mathrm{S}}{\mathrm{N}} \sim (\text{peak star count} - \text{background average})/\text{noise}. \tag{1}$$

Remember that the inverse of S/N is roughly equal to the magnitude uncertainty. If we want to detect color changes in our target we want to keep δb and δg below 0.1 mag (see Figure 1). This implies S/N > 10. In general, you will need to balance the desire for higher S/N with the limitations on the exposure time: 1.) the telescope tracking is not too reliable and you might start getting elongated images at exposure times of $\sim$ 1 minute; 2.) the pulsation period is relatively short and you need a lot of data points to get good light curve coverage (especially since you need to take images in two filters); 3.) make sure none of your targets are close to saturation (stay below 3/4 full-well capacity of 65,000 counts)!

Once you pick the best exposure time, start taking images for your target field alternating between g and b filters. You lab instructor will help you to set up an exposure sequence to automate this process. This will take a long time (since the period could be anywhere from 1-3 hours long, so alternate who is taking the data), but don't walk away from the telescope. You will want to monitor observing conditions, focus, and pointing throughout. **If the star drifts more than a few arcseconds, it might make analysis of this data considerably more challenging, so pay attention.** Careful observations not only improve your science, but will save you lots of time and headache down the road. While you are waiting, you can also try to do rough photometry of your target with Maxim DL to see if it is behaving as it should.

While you are taking data, it is very important to record:

1. name under which an image is saved (make sure filter name is incorporated into the file name),
2. **exact start time** for the exposure,
3. exposure time,
4. filter you used,
4. any other comments on the quality of your image.

Without these records your data will be nearly useless (well, you might be able to get some of it from the FITS headers, but this will take time and things like filter names might not be recorded). Remember that Unix does not like fancy file names, especially ones with spaces in them, so choose your naming convention accordingly.

1.4.4 Dark and Bias Frames

Once you are done taking your science exposures, you will want to take several ($\sim$ 10) bias frames and several ($\sim$ 10) dark frames with the same exposure times as your science images if you have not already done so. Remember to record the dome and outside temperatures as well as your CCD temperatures.

1.4.5 Summary

Ideally, at the end of your observation you should have the following:

- on the order of 100 images of your target field in g and b filters;
- a series of dark frames for every exposure time used in your observations;
- a series of bias frames;
- a series of flat frames for each filter;
- your observing log, containing detailed notes listing times, exposure times, temperatures, airmass, filter and file names for every image saved during your session.

At Brackett, please save your data to your flashdrive. At TMO, set up data transfer to bishop.astro.pomona.edu. You will then be able to 'scp' your files from bishop to the computers in the astro cluster.

References

Fu, J. N. & Sterken, C. 2003, A&A, 405, 685
Rodriguez E., Lopez-Gonzalez M.J., & Lopez de Coca P. A&A Suppl. Ser. 144, 469

2 Data Analysis

You will use IRAF to do the basic image processing of dark-subtraction and flat-fielding. This manual will give you an outline of these steps, but it is not a comprehensive guide. Please refer to the software manuals on the class page for more information.

2.1 Starting IRAF

Just to remind you, the basic start-up sequence is

xgterm -sb &

ds9 &

cd iraf (in xgterm window)

cl (in xgterm window)

2.2 Initial Data Reduction

2.2.1 Combining Dark and Bias Frames

As a first step, you need to create a median dark and bias frames (using **imcombine**). Dark and bias subtraction are generally performed as separate steps; however, if you have darks that match the integration times of your science exposures, you can skip the bias-subtraction step. It will still be necessary to make a median bias frame, since we will need it for CCD characterization.

To create your median dark (or bias) frame, first create a text list of the dark images you plan to combine. Make sure you combine *only the darks with the same integration time!* The IRAF **imcombine** command can take this list (often referred to as an "@list") as **input**, and create a combined image as **output**: Many IRAF commands can take @lists in place of a comma-separated list (e.g. image1.fits,image2.fits,etc) or a wildcard-specified list (e.g. image*.fits). If you are working on lots of files, this can be very helpful. Most of the other default **imcombine** parameters will be fine, but make sure to set the following: **combine** to 'median' and **reject** to 'avsigclip'. You can now ran **imcombine** by executing

imcombine @*list_of_dark_images* **DARK_med.fits**

When combining many files, even making @list can be time consuming. . So here is a few tricks you can use. Suppose I have a directory full of files among which are the image files I want to process. I can use **ls** command together with > piping command to damp the names of all this file into a text file. For example executing

ls image*.fit > image.list

will create a file **image.list** containing the following
image1.fit
image2.fit
image3.fit
The question mark stands for any one character. You can use * instead to indicate any string of characters.

Now repeat the combining procedure with bias frames.

2.2.2 Dark Subtraction

Once you have created a combined dark frame, you want to subtract it from each of your image and flat frames. You can use **imarith** to do this one at a time:

> imarith image1.fits - DARK_med.fits image1_d.fits

> imarith image2.fits - DARK_med.fits image2_d.fits

> imarith image3.fits - DARK_med.fits image3_d.fits

or write a little IRAF script to do them all at once. If you simply included the above three lines in a text file (called "doall_darksub.cl", for instance), you could execute all three with the following IRAF command:

cl < doall_darksub.cl

Writing this script for a batch of 100s or even 1000s images can be done in minutes with my **ls** trick and an emacs macro. If you haven't mastered these yet, check out the software guides on UNIX and emacs and/or ask your instructor for a quick tutorial.

After the script is done, check that it created the new files and examine those files to make sure everything went well.

2.2.3 Flatfielding

To create normalized median flats, you can again use **imcombine**; however, you will need to create a separate flat for each filter in which you observed. A few of the input parameters (accessed by typing *epar imcombine*) that you'll want to adjust are:

input @*list_of_flat_images*

output to *name_of_the_combined_flat*

combine to 'median'

reject to 'avsigclip'

scale to 'median' or 'mode'

You could also try setting **reject** to 'none' and see which flat looks better. Note that unlike with darks and biases, your flats will likely have non-uniform average countrates, especially when taken at twilight, so they need to be scaled before you can combine them in a meaningful fashion.

Once you created combined flats in all filters, you need to normalize them by dividing your flats by their median or mode value. You can determine both using the IRAF **imstat** command and then divide your flats using the IRAF **imarith** command. Once you've done this, you are ready to flatfield your images.

You can flatten individual exposures (in this case your b-band images) using **imarith**:

> imarith image1_d.fits / flatb_med.fits image1_df.fits

>imarith image2_d.fits / flatb_med.fits image2_df.fits

>imarith image3_d.fits / flatb_med.fits image3_df.fits

or write another IRAF script (doall_flatfield.cl) to do them all at once:
> cl < doall_flatfield.cl

2.3 Determination of CCD Characteristics

Before attempting photometry, you should characterize the CCD, namely determine the CCD gain and read-out noise.

2.3.1 Calculating the Gain

Recall that the gain of a CCD camera is the conversion factor between the number of electrons (and therefore photons) recorded by the CCD and the number of digital units ("counts" or ADU) recorded in the CCD image file:

$$\text{Gain} = \frac{\text{electrons per pixel}}{\text{counts per pixel}}. \tag{2}$$

Knowledge of the gain is necessary for converting counts to real flux units, and for calculating the uncertainty in your photometry results.

The main idea, as discussed in your reading, is to utilize the fact that the photon noise is equal to the square root of the photon signal (since the photon arrival rate can be described by Poisson statistics). But since the number of photons and number of counts are not equal to each other, the noise in count units will *not* equal to the square root of the signal in count units. A reliable recipe for determining the gain based on this idea is outlined below. For more detailed justification of why it works consult your textbook.

You should all have several flat frames for each filter and several bias frames. Examine the flats and pick the ones that show the least variability over the chip. Pick a pair of flats (taken with the same filter) and bias frames that look the best (they should be taken with the same filter) and have similar mean pixel values and standard deviations. To determine those, use the command **imstat**; for example **imstat** *file_name*[**100:200,240:300**] calculates statistics for the image named *file_name* over the square region specified as $x_1 : x_2, y_1 : y_2$ in square brackets. If the region is not specified, the calculation is performed over the entire image. You can also compare modes of the pixel values instead of the means. If **imstat** does not display mode, use **epar imstat** to set the value of **fields** parameter to include **mode** in the comma-separated list. If you are using mode, do the calculation over the entire image.

Let's call the two flats A and B, and follow the steps below.

Step 1. Measure the modes of images A and B, using **imarith**. Call these values F_A and F_B.

Step 2. Calculate the ratio of the modes as $R = F_A/F_B$.

Step 3. Use **imarith** command to multiply image B by the number R. This corrects image B to the same signal level as image A without affecting its noise structure or flat field variation. Note that since we have not yet subtracted the bias offset, scaling flat B scales the bias as well. This is not ideal, but hopefully the bias count level is much smaller than that in the flat, so the error we are introducing is small.

Step 4. Subtract image B from image A. The flat field effects present in both images should be canceled to within the random errors. If you skip this step, the standard deviation of the image will contain flat field variation effect as well as random error.

Step 5. Measure the standard deviation over the same pixel region you used in step 1. Square this number to get the variance, let's call it σ_f^2. .

Step 6. Now repeat steps 1-5 for the two bias frames. Since biases are very smooth, you may get away with using a larger region, but stay away from bright columns. The resulting variance will be called σ_b^2.

Step 7 The gain of the CCD can now be calculated from the following equation:

$$\text{Gain} = \frac{F_A + F_B - B_A - B_B}{\sigma_f^2 - \sigma_b^2}, \tag{3}$$

where B_A and B_B are the mean count levels in the two bias frames. It might seem like the numerator in Eq. (3) has to be divided by 2. In reality, the two terms in the denominator already contains the same factor of two, since the variance is doubled when you subtract one similar image from another.

Compare your results to the values quoted in the camera technical specifications.

2.3.2 Calculating the Read-out noise

As you can guess from the name, the read-out noise is introduced into the image during the read-out process. Imagine trying to read out a pixel with a fixed number of electrons numerous times. Every time this is done, a slightly different value will be inferred, due to inherent noise in the CCD electronics. The RMS variability in the resulting values (measured in electrons per pixel) is the read-out noise.

It is easy to see that the read noise is essentially the standard deviation of a single bias frame, corrected for the intrinsic variation in the bias level from pixel to pixel. This correction is done by subtracting two bias frames. With this, the equation for determining the read-out noise is

$$\text{Read Noise} = \text{Gain} \cdot \frac{\sigma_b}{\sqrt{2}}, \tag{4}$$

where σ_b was calculated in the previous section, and a factor of $\sqrt{2}$ corrects for the doubling of the variance during image subtraction.

The specs for Apogee claim total system noise of < 10 electrons RMS. Are your results consistent with this claim?

2.4 Photometry with IMEXAMINE

The main goal of this lab is to learn how to measure stellar magnitudes. The simplest way to determine instrumental magnitudes for your targets is to use **imexamine**. In general, this command is not designed to do serious photometric measurements, but it will suffice for this lab. However, if you are familiar with **phot** and prefer to use it instead, feel free to do so. Brief guidelines are given in §2.5 below.

2.4.1 Getting to Know IMEXAMINE

The main goal of this lab is to learn how to measure photometric stellar magnitudes. To do this you will be using the IRAF command **imexamine**. We already tried it once in class, and there is a nice description of this command on our course webpage. Please read it before you begin work. Note that sometimes **imexamine** exits the interactive mode by itself. If this happens, try to restart it; if it continues to misbehave, restart IRAF.

Start by choosing an image and identifying your target object and two comparison stars (use your finding charts for help). Run **imexamine** and check the radial profile of your target stars by placing the cursor on a star and typing 'r'. The averaged radial profile will appear in the new graphics window. Estimate the radius where the count rate falls to half of its peak value (HWHM); multiplying this value by 3 will give you a good aperture radius. Repeat this for several other images, to make sure that the stellar sizes are consistent from image to image. If you find variability, pick the largest radius.

Now quit **imexamine** and type **epar rimexam** to set the parameters for aperture photometry. Leave everything at the default values except for setting **radius** to the value you picked and **iteration** to 1. This last change is important to prevent **imexamine** from adjusting the aperture radius value for each star (think why picking different aperture values between the target and comparison stars would not be a good thing when doing differential photometry). The other two important parameters are **buffer** and **width** which set the width of the buffer zone between the aperture and the sky annulus and the width of the sky annulus, respectively. By default they are set to 5, leave them at these values unless you are feeling adventurous.

You will now be able to get a pretty good determination of instrumental stellar magnitudes by running **imexamine** again, placing a cursor on your star and typing 'a'. Look at the help file by typing **help imexamine** to see a detailed description of what 'a' does. The short summary is that it sums the counts inside the aperture defined by the **radius** parameter and subtracts from it the sky contribution estimated from the sky annulus set by the **buffer** and **width** parameters. The magnitude is set to magnitude = magzero $- 2.5 \log_{10}$ (flux), where **flux** is the number of stellar counts and **magzero** is the user defined magnitude zero point. Since we will be doing relative photometry, just leave **magzero** at its default value. Of the output

from 'a' you need to concentrate on columns: 1 (stellar x-coordinate), 2 (stellar y-coordinate), 5 (radius used for photometry), 6 (magnitude), 7 (flux, i.e. stellar counts inside the aperture), 8 (mean background counts per pixel).

It is a good idea to try to vary aperture parameters around your chosen values to get an idea how much the derived magnitude depends on your choices (hopefully not too much!).

2.4.2 Running Batch Photometry

You will have several dozen images to analyze in each filter. Examine your log files and discard (mv into a different directory) the files which you do not expect to use (for example one year Prof. Esin's team had so much fun arguing about fantasy literature that they let the target move clean out of the field of view!).

Now put the names of all your good flat-fielded images taken with the same filter in a single file (again using **ls** command as described in §2.2.3 above) and giving the file name as input to **imexamine**. For example, let's say you created a file named **list** which contains all the file names of my images, one per line. This is what you would do next:

Step 1: Type **epar imexamine** and set the parameter **logfile** to the name of the file in which imexamine will record all the photometry information (a copy of the screen output). Set the parameter **keeplog** to **yes**.

Step 2: Type **imexamine @list** (do not forget the '@'!)

Step 3: Make sure your cursor is in ds9 and type **w**. This will open the log file

Step 4: Place the cursor over your target star and type **a** to compute its magnitude

Step 5: When you are done with an image, type **n** to load the next image and go back to step 4.

Step 6: When you go through all the files, type **q** to exit imexamine. Keep track on the file names displayed in the upper left corner of ds9, because left to itself, **imexamine** will go back to the first image on your list, once you go through all the other files. You can quit at any time.

First try to go through just 2-3 files and examine you log file using unix command **more** or loading it into emacs (you will have to stretch your windows to avoid wrapping lines). When you see what format the data is in you will have to decide on the strategy. You can go about getting all the photometry in two ways.

One way is for every image to get magnitudes for all your stars (one target and two standards). Make sure you examine them in the same order for each image, to make sure you know which is which! This method will probably take you the least amount of time. However, all the stars will be mixed up together and the resulting data set will be hard to use.

Another way is to go through all the images several times and obtain photometry for one star at a time. This will take you a little bit longer, but all the data will be arranged neatly in separate files. Make sure you rename the log file each time you run **imexamine**, otherwise the new data will get appended to the old data (or worse yet, overwrite the old data)! This is the method I prefer, since this will allow you to easily input the data into excel and compute magnitude differences. In the rest of this section I will assume that your data is in three different files. If you prefer the first method, modify my instructions accordingly.

2.5 Photometry with PHOT

If you followed the instructions in §2.4 above, skip to §2.6 IRAF task **phot** is the one usually used when measuring stellar magnitudes. You can use **phot** in interactive mode, whereby you go into the image and select stars on each frame that you want measured. This is tedious after more than a few frames, so you will run this non-interactively. The drawback is that all the images should first be shifted so that your target stars have the same (x,y) coordinates in every image.

2.5.1 Image Alignment

You will use the IRAF command **imalign** to align all your images. **Imalign** takes as input:

- a list of images to shift
- a reference image
- a reference coordinates file that it will use to compute the shifts
- a list of output shifted images

Step 1. Display all images that you plan to align and step quickly through them all to get a sense of how much the telescope pointing was drifting over the course of your observations. If you had a large jump in the middle of the night, note the image number. You may need to align your images in sets and then align the sets afterwards.

Step 2. Create a text list of all of the imags you want to align as well as an output list that matches the input list:

ls -1 *fits > input.list

ls -1 *fits | awk '{print "sh_"$1}' > input_sh.list

The first command creates the input list. The second command takes the input list and appends the prefix "sh_" to every file name, creating an output list.

Step 3. Display in DS9, the first image in your list, this will be your reference image. Then run **imexamine** on it, and use the "x" keystroke to create a list of pixel coordinates for 5-10 bright stars.

imexam *name_of_reference_image* **logfile=imexam.log keeplog+**

Note that this is a way to run a command with new parameters without explicitely setting the parameters through **epar imexamine**. When ran like this, the new parameter values are *not* saved for next time.

Step 4. Run a first pass with **imalign** with the *shiftim* option turned off. You will need to increase the size of the *bigbox* and *boxsize* from their default values in order to find your drifting stars. Do this gradually (100 pixel steps in *bigbox*) and a max of 25-50 pixels in *boxsize*. You will know if you are large enough when **imalign** is able to calculate shifts for all of your input frames. Once all frame shifts are calculated, rerun **imalign** with *shiftim* turned on.

Step 5. Flip through your images to see if they look more aligned. Run a second pass with **imalign** on the new shifted images and the default *boxsize* and *bigbox* values. At this point, your images *should* be well aligned. Use DS9 to flip through them again and confirm this to be the case.

2.5.2 Photometry

Now we are ready to calculate stellar magnitudes. Since you will be running **phot** non-interactively, you need to be careful about your input parameter selection.

Step 1. Load **phot** package if you haven't already, it is in the **noao** → **digi** → **apphot** IRAF package.

Step 2. Display your combined image and use **imexam** again to create a list of stars on which you want photometry performed.

Step 3. Edit the *photpars* parameters to use a range of aperture sizes for your photometry. What is a good radius? One way to get an estimate of this is to run **imexamine** and check the radial profile of your target stars by placing the cursor on a star and typing 'r'. The averaged radial profile will appear in the

new graphics window. Pick the smallest radius which contains most of the stellar counts and write it down. Repeat this for several other images, to make sure that the stellar sizes are consistent from image to image. If you find variability, pick the largest radius.

If you want **phot** to calculate realistic magnitude uncertainties, you need to also set the gain parameter (**epadu**) and read noise (**readnoi**) parameter to the values you determine (see §2.3). These can be set by invoking **epar datapars**.

Step 4. Run **phot** on your list of aligned images. The short summary is that it sums the counts inside the aperture defined by the **radius** parameter and subtracts from it the sky contribution estimated from the sky annulus set by the *fitskypars* parameter list. The magnitude is set to magnitude = magzero $- 2.5 \log_{10}$ (flux), where **flux** is the number of stellar counts and **magzero** is the user defined magnitude zero point. Since we will be doing relative photometry, just leave **magzero** at its default value.

Step 5. Take a look at the output from **phot**. It is a bit of a mess. The IRAF **tdump** or **tprint** commands may be helpful here.

At the end of this procedure you end up with a list of stellar magnitudes with uncertainties for your target and comparison star.

2.6 Timing the Observations

Once you are done with photometry you will need to determine and record time of observation for each data point. The time of observation can be most easily obtained from the headers of your images. Using **hselect** is a good way to extract the relevant information from the headers of your files: Use **epar hselect** or try the following command:

hselect *fits $I,TIME-OBS yes > timeobs.log

VERY IMPORTANT: Make sure that the order of the files is the same as the order of the file names in your batch file described in §2.4.2; otherwise your times and your photometry will not agree. It might be safer to use the file listing the images (@list) rather than *fits.

If the times look strange, remember these correspond to UT, not local LA time. The resulting values are in sexagesimal format which is not always the most convenient format for plotting. You will want to convert these to hours or minutes when combining the data in excel (see below).

At this point you are now done with IRAF as far as photometry is concerned. All you have to do is to clean up your data files in emacs (see the emacs tutorial for the list of useful commands) and to combine your data files and your timeobs.log.

2.7 Astrophysical Analysis

2.7.1 Number Crunching

You will need a program like Excel to analyze your data. On the astro machines there is an Excel-like program which can be invoked by typing **ooffice *file_name.csv* &** on the command line (the .csv suffix is necessary for the program to realize it needs excel and not just a text editor; so just use **mv** command to change the names of your data files). I am not sure whether the new version has plotting capabilities, but it can do number crunching for you. Alternatively, you can simply transfer all the data to your regular HMC account and analyze it there.

Matlab is also available on astro machines (type **matlab &** to start it) and you can use it for plotting. Another possibility is to use SuperMongo (type **sm**), which is a very nice and simple plotting routine. There is a short tutorial on it on our webpage.

2.7.2 Light Curves

Your standard stars should have measured B and V magnitudes. These are not the exactly same your b and g magnitudes, since our filters are slightly different than the standard Johnson set. If you are feeling ambitious, you you can perform a formal transformation from B and V to b and g magnitudes, as described in Jester et al. (2005) (www.sdss.org/dr6/algorithms/sdssUBVRITransform.html). Otherwise, for the purpose of this lab you can ignore the difference in filter band-passes. Use your standard star(s) to calculate B and V magnitudes for CY Aqr, and construct light curves showing variations in b, g and $b-g$ as a function of time. When plotting magnitudes vs. time, *do not forget to invert your y-axis*, since smaller magnitudes correspond to larger fluxes.

Using **imexamine** is not the greatest way to do photometry because it does not give you error bars. To compensate for this, you will need to compute a couple of representative error bars for your data, taking into account read-out noise of the CCD, thermal and sky background noise and counting statistics of the star itself. You have all the necessary information, from the photometry results and your gain and read noise calculations. For instructions on how to determine S/N, review our discussion in lecture and in your textbook. Do not forget to convert counts to electrons (multiply by the gain)!

Total electron number is proportional to photon flux, the fractional uncertainty in flux is practically equivalent to $\pm$ uncertainty in magnitudes. Thus, your final errorbars will be equal to $\delta m = \delta F/F$. Plot these sample error bars on your light curve to show how good (or bad) your data is.

Do not include the uncertainty in the standard star magnitudes in your errorbar calculations. I suspect that these are mostly *systematic* rather than random errors. This means that they will move your lightcurve up or down, but will *not* contribute to the spread of the data points.

Compare your results to the light curves for CY Aqr shown in Fu & Sterken (2003).

2.8 Lab Report

Please attach a photocopy of your observing log to your report, but also summarize your observations in the table that gives the number of images taken in each filter and your exposure times. You do not need to copy this manual by giving a step by step description of the data analysis. However, you do need to describe things that are not obvious, like how many and which standard stars you used, how you calculated differential photometry values, how you computed the errorbars, etc. Do not forget to include your values for the CCD gain and read-out noise.

You also need to include a discussion of the light curve of your star in relation to the physical mechanism that is driving its variability. This part is the real astrophysics!

Some issues you should talk about:

- What is the correlation between color and amplitude changes? What does it imply about the relationship between radius, temperature and luminosity changes over the pulsation period?
- Is the shape and amplitude of the light curve different in different filters? If there is a difference, what is the reason behind it?

If you have the time, try to come up with ways to quantify the change in luminosity, temperature and radius for your target star.