Performing Photometry on HDI Data With AstroImageJ Using Lippy's HDI Tools

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On January 12, 2017 Michael Richmond, Jen Connelly, Ekta Shah, Trent Seelig, and I observed the cataclysmic variable star HT Cas with the Half Degree Imager (HDI) on the WIYN 0.9m telescope. The weather conditions were very poor due to variable cloud cover. We took repeated measurement of 3 to 6 seconds in length with a Harris R-band filter with the camera in 1-amp mode.

In order to produce a light curve of this object I developed a set of macros in AstroImageJ to reduce the data. A macro is just a short Java script that uses the built in capabilities of AstroImageJ to automate a process. This documentation will lead you through how I produced a light curve of HT Cas but is applicable for any variable star data. The macros are also useful for data reduction of any HDI data.

This document will make use of a few macros which should be very straightforward to use but require specific setup. I will go through the required steps but each individual macro is commented and includes information in its header and the README about how to use it. They are just .txt files and can be opened with any text editor. Place these macros within the **macros** folder of your AstroImageJ installation.

Requirements

I used AstroImageJ version 3.2.0 which includes ImageJ version 1.47i on a MacBook Pro version 10.9.5 running Mavericks. AstroImageJ is available here:

http://www.astro.louisville.edu/software/astroimagej/installation_packages/

and the download is very straightforward. Versions of AstroImageJ exist for Linux, Mac, and Windows systems.

For clarity, any folders or clickable items discussed in this document are **bolded** and any macro you will need to use will be in `this font`.

AstroImageJ will only work on simplified FITS images. The FITS images that are output by HDI are not in this format and must be converted from a "Header Header Image" type file to a "Header Image" type file. To do this, you must run *fitsconv.csh* on emerald before grabbing your data and working with it. If you have no idea what I'm talking about, read this page:

https://www.noao.edu/0.9m/observe/hdi/hdi_manual.html#convert

1. Running A Macro

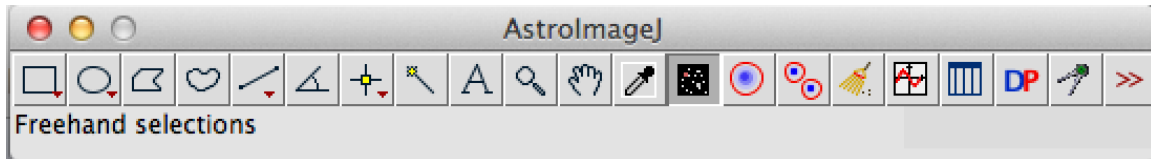To run a macro, first open AstroImageJ. This box will appear:

Figure 1: AstroImageJ's main toolbox display.

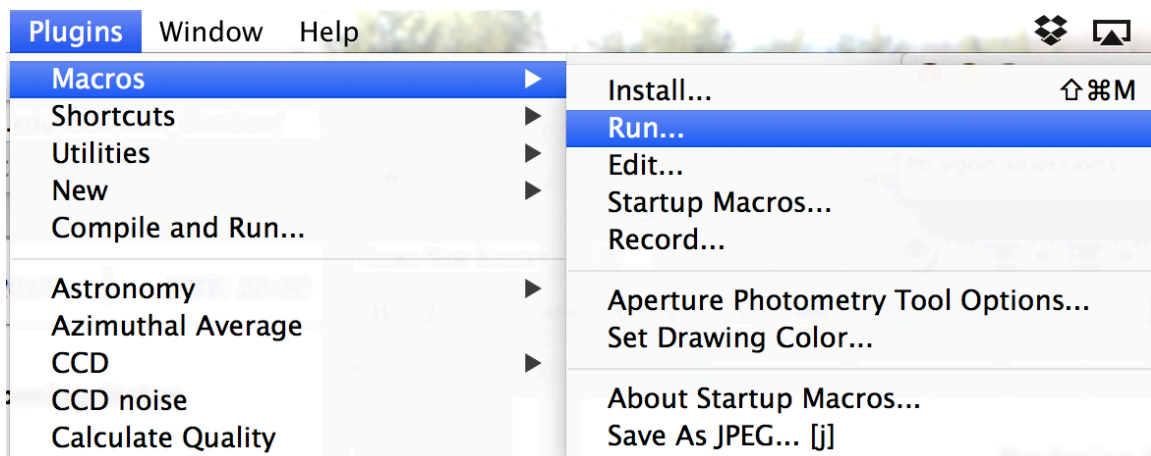Go to the Navigation Bar on the top of the screen and select **Plugins → Macros → Run…**

Figure 2: How to run a macro in AstroImageJ.

Selecting **Run…** will bring up the Finder window and ask you to select a macro. Select **Applications**, find your **AstroImageJ** folder, then **macros**, then find **Lippys-HDI-tools**. Inside you will find macros to reduce HDI images and characterize the 0.9m WIYN telescope. Select the macro you would like to use and click **Open** on the bottom right. If at any point you wish to stop a macro you can press the escape button on your keyboard to kill the current running process in AstroImageJ. If you are running a macro that has several different parts to it, you may need to press the escape key a few times to actually end the program.

NOTE: DO NOT click on any image that pops up as a result of a macro until the macro has finished. The macros work on the currently selected image and if you change which image is selected it will break or cause incorrect results. So once you click **Open**, just sit back and watch the process! You can keep track of what exactly is happening by

watching the "Log" window that will appear once a macro starts running. If a prompt comes up and you are unsure what it means or what to do, try checking the Log window which may have popped up in the background behind other AstroImageJ windows.
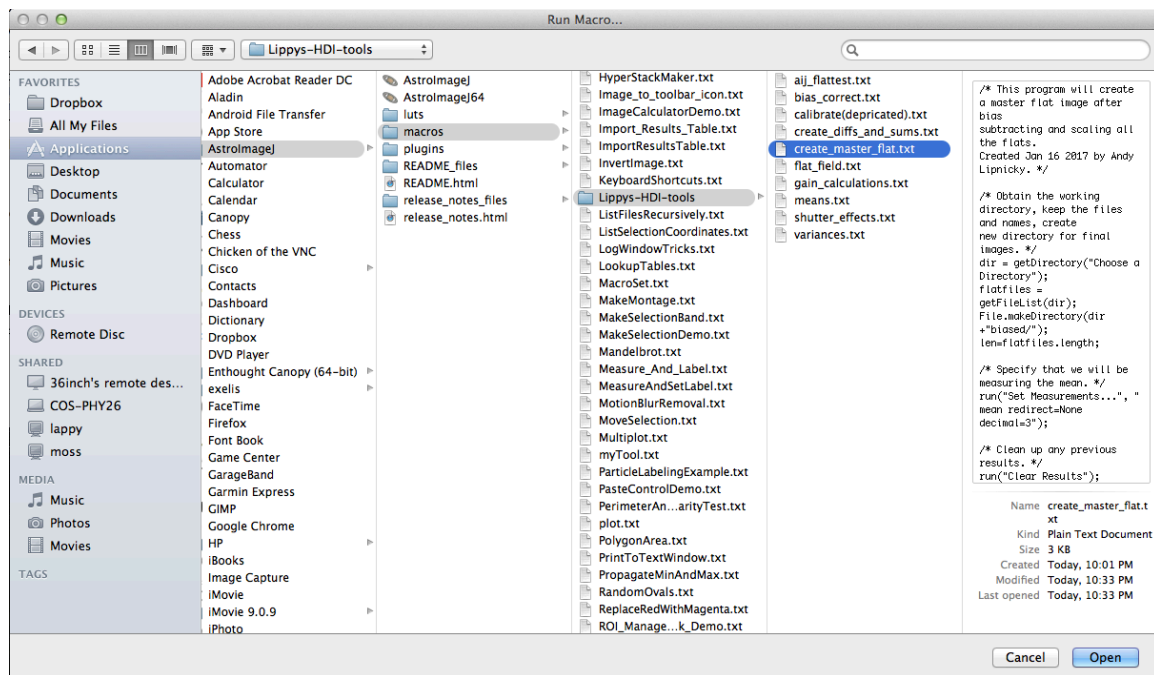

Figure 3: Navigating to where macros are located in the file system.

2. Reduction

The first step to any photometry is to bias and dark subtract and flat field your images. Specifically with the WIYN 0.9m HDI camera it has been found that for exposures of 500 seconds the dark current is about 1 e⁻ which means that for our observations dark current is not an issue. If you don't believe me, you should check out this technical note on Michael Richmond's website:

http://spiff.rit.edu/richmond/wiyn/technotes/tech_6/tech_6.html

Therefore, we only need to worry about bias subtracting and flat fielding.

To reduce our data using macros we first must organize our data. Place all the images you wish to correct into their own folder. I suggest placing your time series observations in one folder (here: **HT_Cas**) and your flat field images in another (here: **r_flats**).

2.1 Bias Subtraction

Each image taken with the HDI camera has an overscan region on the right-hand and upper edges. These regions are filled with "virtual pixels" in that they don't exist physically. This happens because as charge is read off the CCD from the amplifier, it

continues to read charge for a few more pixels after the entire image has been read out. This then measures the signal introduced into each image by the amplifier and the electronics. The overscan region therefore gives us a good measure of the bias level in each individual image.
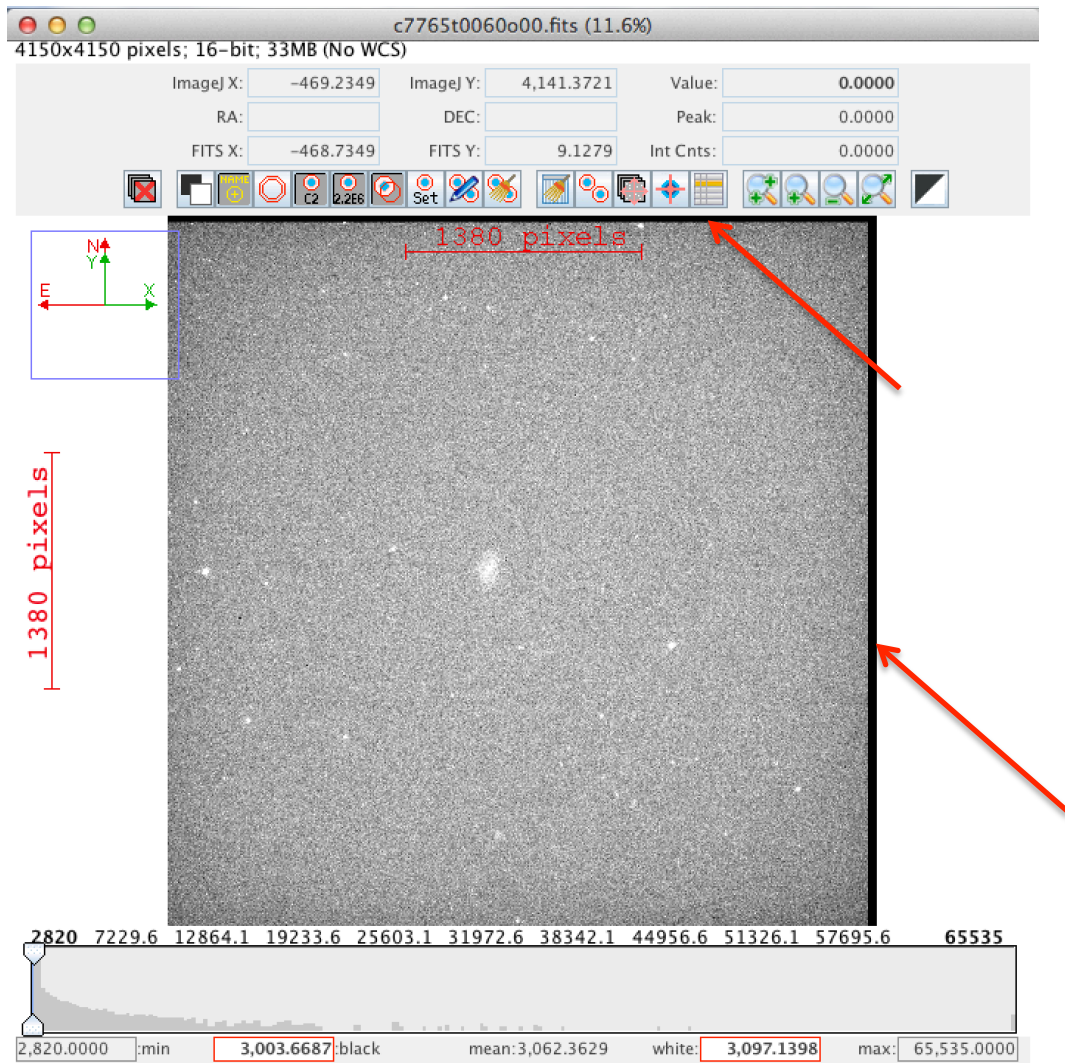

Figure 4: Image taken of NGC 2712. The overscan region is the black edge seen along the top and right-hand sides of the image.

Another way to measure the bias level is to take a set of 0 second exposures at the beginning and end of the night. These images are just read off the chip without actually opening the shutter and, therefore, just give the signal introduced by the amplifier and the electronics. However, if the amplifier is unstable and does not hold a steady bias level it can change throughout the night which will introduce error into your final image analysis. For the HDI camera, this is not the best option since the bias level fluctuates slightly from image to image.

So, our first step is to measure the mean counts in the overscan regions. Once the mean is found, we can subtract the entire image by that value to remove the effect of bias. This must be done to both our flat field images and our observations. The macro named `bias_correct` will do this for any set of data; although, the other reduction macros also include bias corrections already. So run this macro **only** if you wish to see the difference between biased and non-biased data. You may also run into a situation where you do not have dome flats and can only use bias subtraction. In that case `bias_correct` will be the only reduction tool that you can use.

`bias_correct` will immediately prompt you to select a directory to work on, this directory must only contain FITS images otherwise it will break. Once you select a folder it will immediately begin bias subtracting the images. While `bias_correct` is working, it will open the images in the folder, find the mean, perform the subtraction, save the image to a new folder it creates called **biased**, then close the image and move on to the next one. A log window and a measurement window will open as well. Watch the log window to see the progress, it will report the average bias level and tell you once it is finished.

2.2 Create A Master Flat

Flat field images are images taken of a uniformly illuminated surface such as a white screen in the dome or the sky near sunset/sunrise. Since the field you are observing should be evenly illuminated, any variations in the image will be caused by defects in the telescope or filter. This includes any dust/debris that has settled on the mirror or the filter and any variations in sensitivity across the chip. We will eventually divide all our observations by a "master" flat in order to remove these effects and create a science image.

It is always good practice to take about 10 flat field images in each filter that will be used during your observations and median combine them into a single master flat image. By median combining many images, we can remove the effects of transient noise such as cosmic rays and/or stars that show up in sky flats so that we are left with only the effects caused by the telescope or filter.

If you followed the previous directions, you should have a folder that exclusively contains the flat field images that you will need. Run the macro `create_master_flat`. It will immediately prompt you to select the folder containing the flat field images.

The macro will begin by bias subtracting all the images. Next it will scale all the flats to the first image by calculating the mean of the illuminated area of both images and applying the ratio. This is done to remove any variations in the brightness of the lamps or variations in the sky brightness as the sun set/rose. Once all the images have been scaled correctly, they are combined into a "Stack." AstroImageJ allows you to perform many operations on Stacks of images, which will be important later when creating a lightcurve, but for now we will use the Stack to combine all our images into a single master flat field. After median combining the flats, the mean of the light collecting area is calculated and the image is normalized to this value. The master flat is then saved in the same

directory as "masterflat.fits" and opened for you to inspect. You may wish to rename this file to something more useful such as "r_masterflat.fits" so that it is more clear to you later which filter it corresponds to.
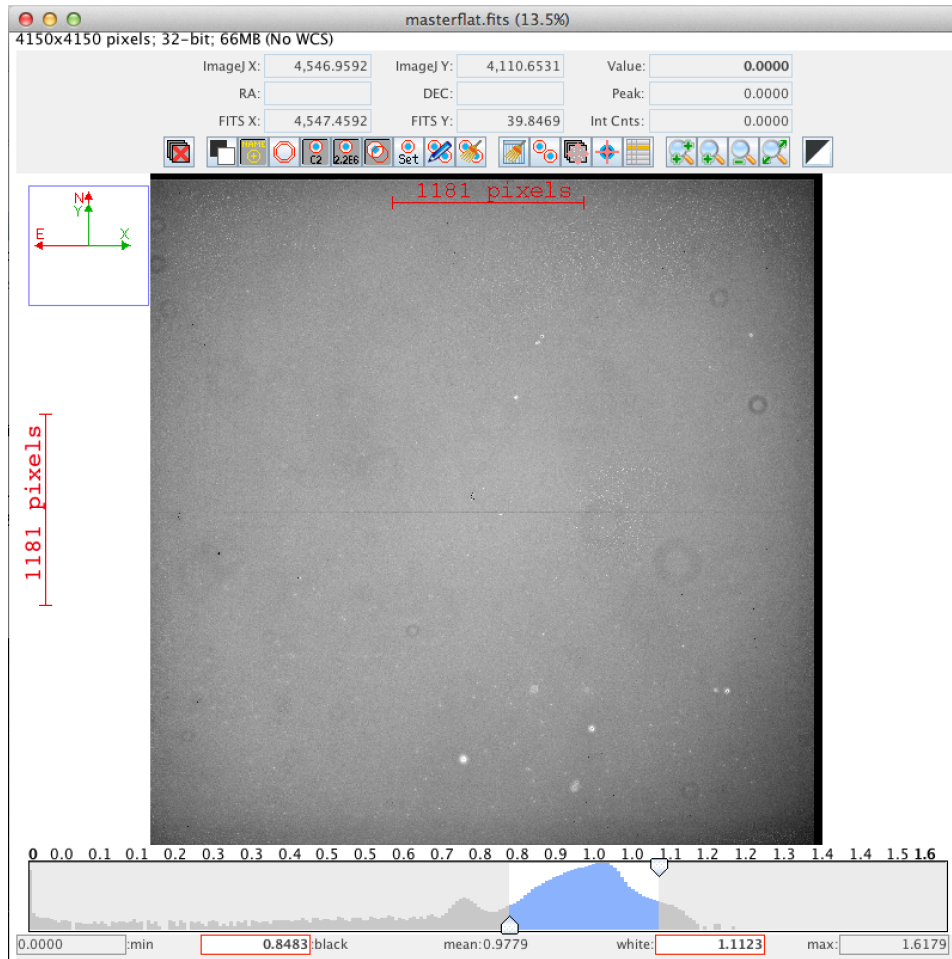

Figure 5: A Harris R-band master flat field image created by the `create_master_flat` macro. The presence of dust can be easily seen as rings in the image.

If this isn't your first time using AstroImageJ, you may know that it already has a nifty feature for creating master flats! BUT! Be warned, when their pipeline normalizes the flat field images it takes the mean of the entire image instead of just the illuminated area. It therefore includes the overscan region which has many pixels with counts that will be more than 2,000 counts below the rest of the image. This has the effect of lowering the mean and producing an over bright master flat. So, for the best results, use the `create_master_flat` macro instead.

2.3 Flat Field Divide The Data

Now that we have biased subtracted our observations and created a master flat, it is time to flat field divide our observations. Once this is done we will have removed the effects of the electronics and the effects of telescope defects. This means the resulting images of

our targets should only contain signal from photons entering the telescope so we can finally do some science! Yay!

To flat field your observations, open your master flat field image and then run the `flat_field` macro. It will immediately prompt you to select the folder containing all the images (here: **HT_Cas**). The macro will bias subtract the image, divide by the master flat, trim off the overscan region, and save the reduced image in a folder named **calibrated**.

2.4 Shortcut

If this isn't your first time calibrating data and you wish to just get the results, you can run the `calibrate` macro which will just run the above steps quickly back-to-back. It is much, much quicker than running the macros individually because it makes use of "batch mode" which suppresses the images from being displayed. When you run `calibrate` it will immediately prompt you to select the folder that contains the flat field images to create a master flat. Once that process has completed it will then prompt you to select the folder that contains the data you wish to reduce. The reduced and trimmed images will be placed in a folder named **calibrated** inside the folder which contains the raw data.

3. Photometry - Making A Light Curve

Now, lets make a lightcurve! For this we will actually use some of the terrific tools included in AstroImageJ. The first step is to load the calibrated time series data into AstroImageJ as a Stack. This is done by selecting **File → Import → Image Sequence…**
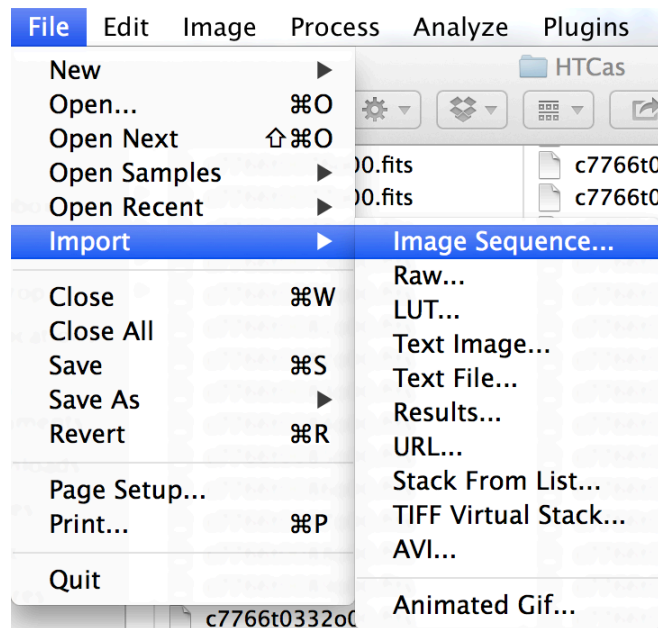
Figure 6: Importing a set of images as a Stack.

After you click on **Image Sequence…** a window will pop up that will show the number of images in the Stack and give you some options. Make sure **Sort names numerically**

and **Use virtual stack** are selected then press **OK**. It is essential that you select **Use virtual stack** because this causes AstroImageJ to know the location of the image without actually opening it. It also will be a lot smarter about managing memory as you perform calculations on the Stack later. If you have a large number of images in your Stack and you did not select **Use virtual stack**, your computer will quickly run out of memory.
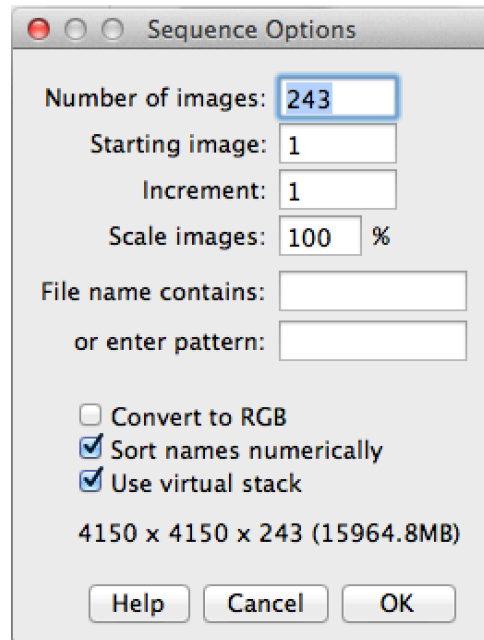

Figure 7: Importing a set of images as a Stack. Make sure to select **Use virtual stack** or your computer is likely to run out of memory.

The Stack will then appear in a window and will display the first image. You may scroll through the images in the stack by using the left and right arrow keys.

Now that we have our time series data in a Stack, we can perform multi-aperture photometry. This is done by selecting the **perform multi-aperture photometry** button.
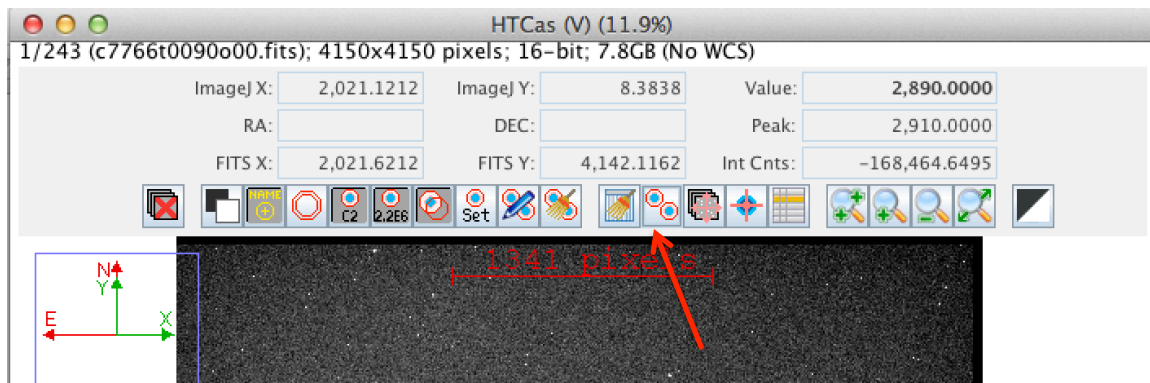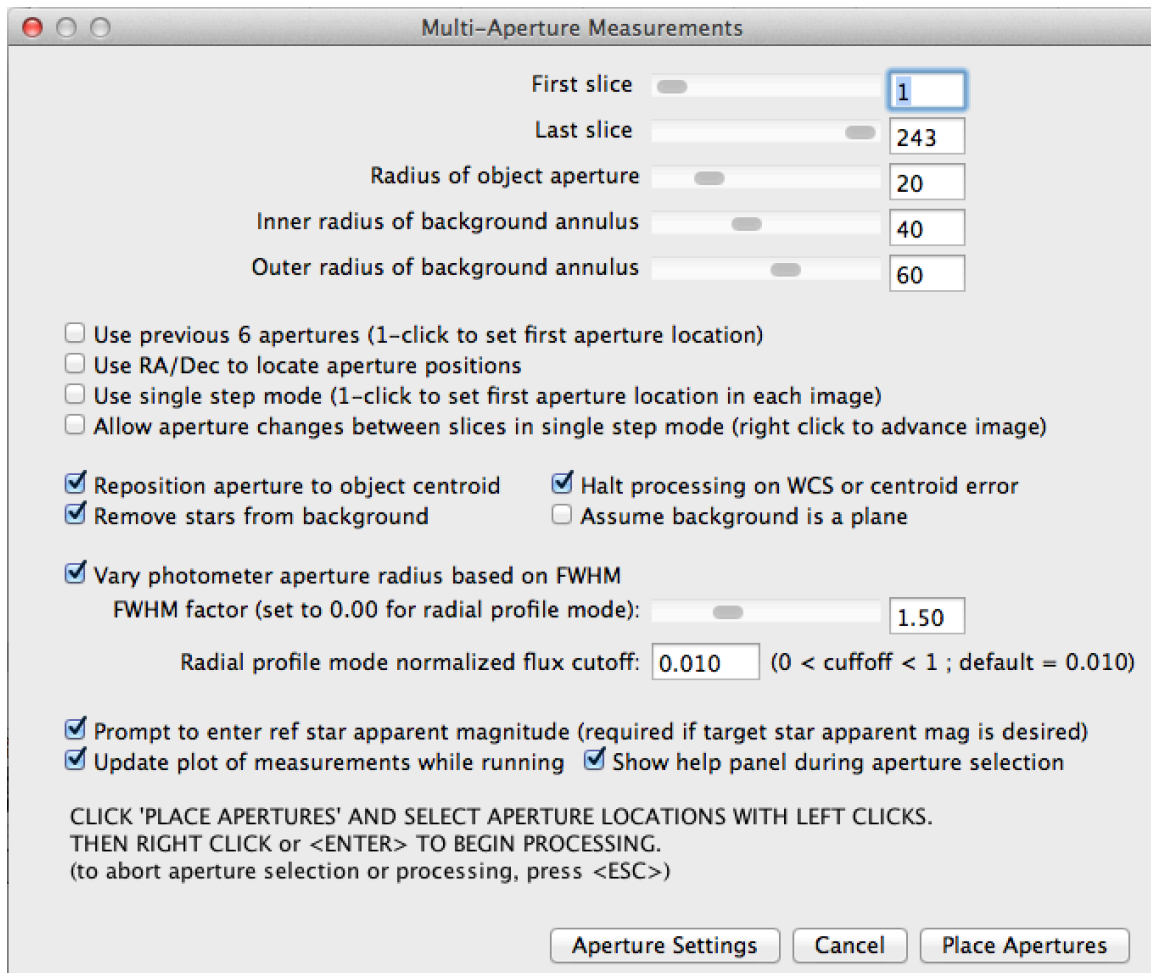
Figure 8: The **perform multi-aperture photometry** button.

The next window that pops up will give you many options for how you would like to place apertures and what you would like them to do. Ensure that you select the same options that are displayed in the next figure or understand your choices.

Figure 9: Multi-Aperture Measurements setup window.

There is a lot going on here so lets go through each option:

- Ensure that the **First slice** and the **Last slice** correspond to the first and last image in your Stack; if you were scrolling through the images they may not be set correctly.
- For the **Radius of object aperture** we need to select an aperture size in pixels that is large enough to incorporate the entire target and not too much background sky. It must also be large enough for the comparison stars we will be using which may be brighter than our target and therefore cover more pixels. Also, for this data set, our measurements suffered from intermittent clouds which caused the PSFs of the stars to grow. Choose a radius that makes most sense to you.
- The **Inner** and **Outer radii for the background annuli** are probably good at their default values; although, if you have a crowded field you may need to make adjustments.

- In general, you do not want **Use previous N apertures** unless you know exactly what was done before.
- If your images do not have WCS solutions make sure **Use RA/Dec to locate aperture positions** is unchecked
- If you have dithered between images or know that the guide star was lost or know that for some reason the stars in your images are not located in the same general area, then you will want to select **Use single step mode**. Otherwise, AstroImageJ does a good job of finding your stars from image to image.
- We will want to keep looking at the same stars in each frame so make sure **Allow aperture changes in single step mode** is unchecked.
- Make sure that **Reposition aperture to object centroid** is checked so that AstroImageJ measures the targets well by making small adjustments to the aperture location.
- Make sure that **Remove stars from background** is checked. This will ignore any stars that happen to be in the region between the inner and outer background annuli so that an accurate measurement of the background can be made.
- Make sure that **Halt processing on WCS or centroid error** is checked. If there is a problem with the data and AstroImageJ loses track of the target, it will stop rather than continuing to run through the Stack producing bogus results.
- Make sure that **Assume background is a plane** is unchecked since this will give the background a constant value.
- Since the seeing for our data was highly variable from image to image because of cloud cover, it was important that **Vary photometer aperture radius based on FWHM** was checked. In general I think that this is an important consideration. If you select a small aperture radius initially, this can help avoid errors introduced by poor seeing. In general it is a good idea to have an object aperture that is 1.5 – 2 times the size of the FWHM.
- If you know the catalogue apparent magnitudes of other stars in the field then you should definitely check **Prompt to enter ref star apparent magnitude**. If you do then AstroImageJ will calculate the apparent magnitude of your target. If you don't have this information right now, you can get the apparent magnitude later from the solutions AstroImageJ will output but it will take a bit of work on your part. (So take some time to load up a catalogue in Aladin and get the magnitudes right now.)
- Make sure **Update plot of measurements while running** is checked. This is the most fun part of using AstroImageJ since you get to see your light curve develop as it processes your data.
- Finally! Make sure **Show help panel during aperture selection** is checked so that you have on screen help during the next step.

Once you are happy with your selections, click **Place Apertures**. The following window will pop up instructing you what to do:
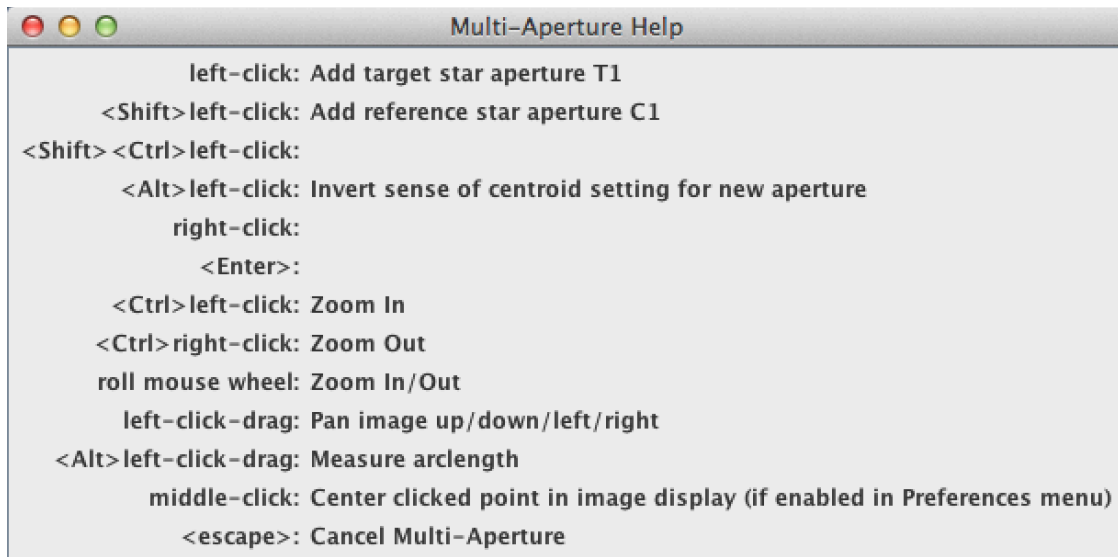
Figure 10: Multi-Aperture Help window displaying information about selecting the target star.

First, left click on the target star. The Multi-Aperture Help window will change to display information about how to add comparison stars.
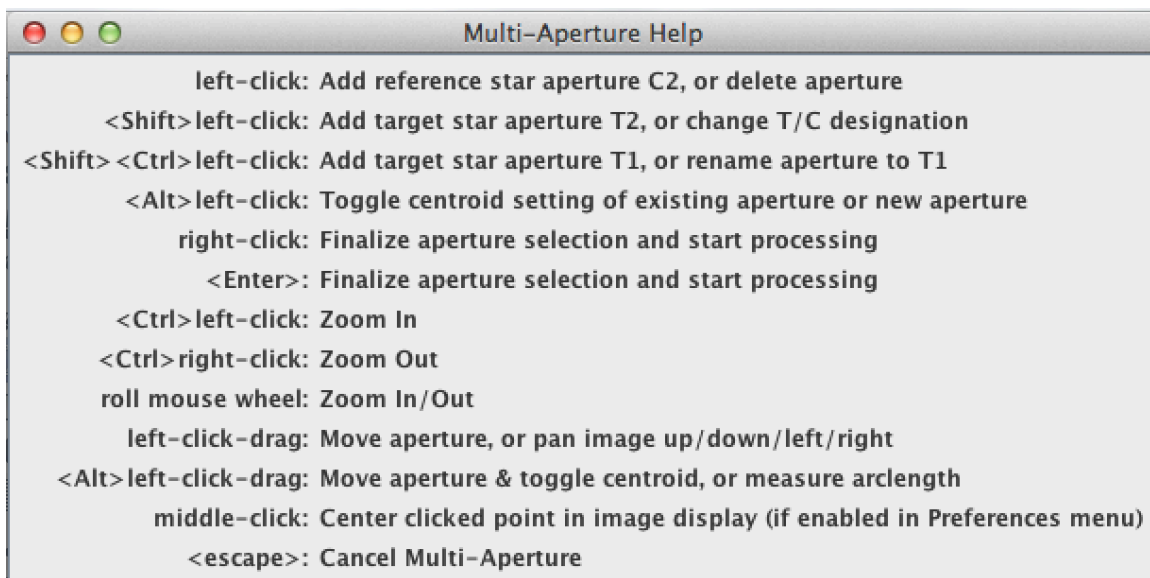

Figure 11: Multi-Aperture Help window displaying information about selecting comparison stars.

To select comparison stars, simply left-click on stars in the image. To help you select good stars you may zoom in by scrolling. You can then pan around the image by clicking and dragging. It is good to have about 5 – 8 reference stars in your analysis. More is better but only if they are sufficiently bright without being too bright. You should select reference stars that are about the same brightness as the target. This will ensure that they are not over exposed and ensure that they are not lost in some images if the seeing is especially poor (remember that if AstroImageJ loses a source it will abort). If you selected **Prompt to enter ref star apparent magnitude** earlier you will see a window

pop up after each comparison star selection. It is also possible to select more than one target star by holding the Shift key and left clicking on another star. You can also remove previous selections by clicking on the object again if you decide it was a bad choice.
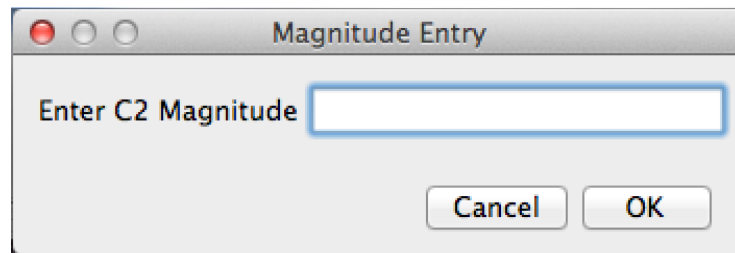

Figure 12: If you selected **Prompt to enter ref star apparent magnitude**, this window will appear after each comparison star selection.

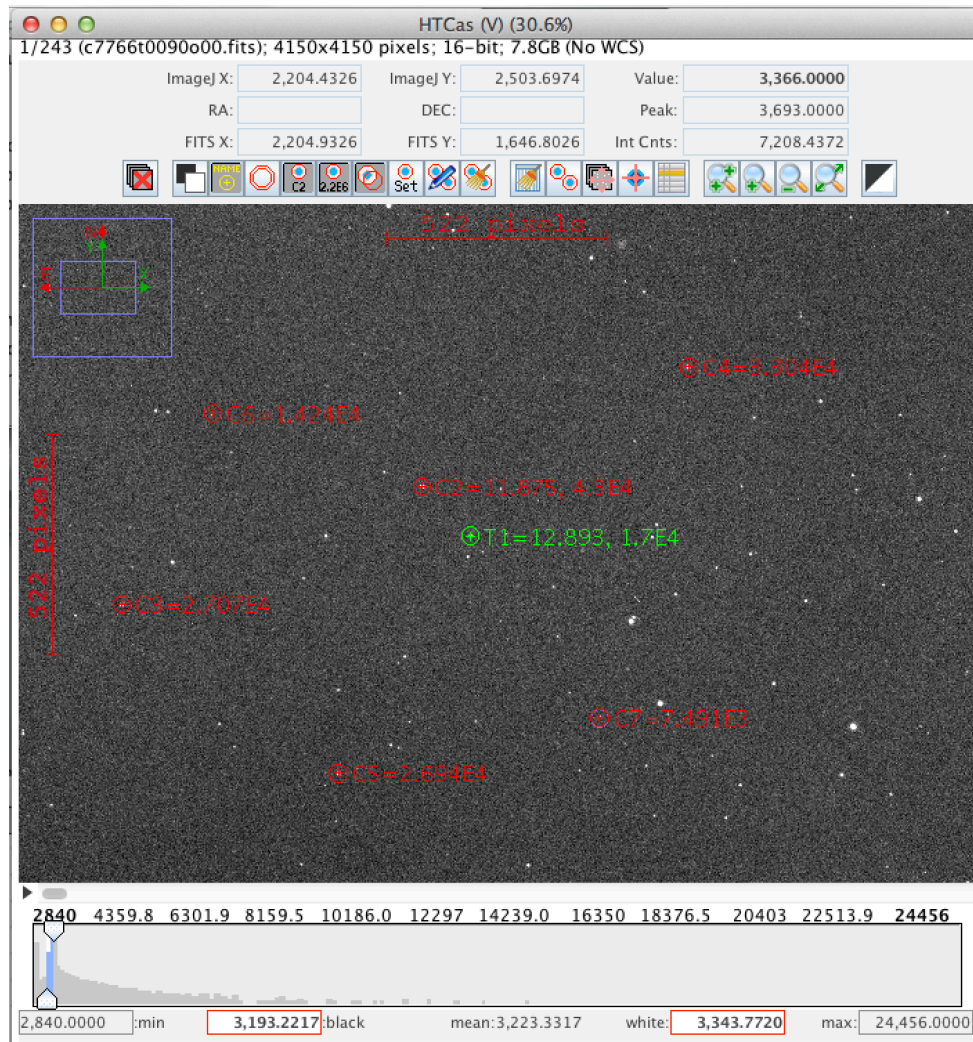Once you are satisfied with the comparison stars you have selected, right click on the image.

Figure 13: Target and Comparison stars chosen for multi-aperture photometry.

This will cause the program to start going through the Stack image by image and performing photometry. Many, many windows will pop up but eventually AstroImageJ will start plotting the relative flux of the target star for each image and you will get to watch your light curve develop as it processes.
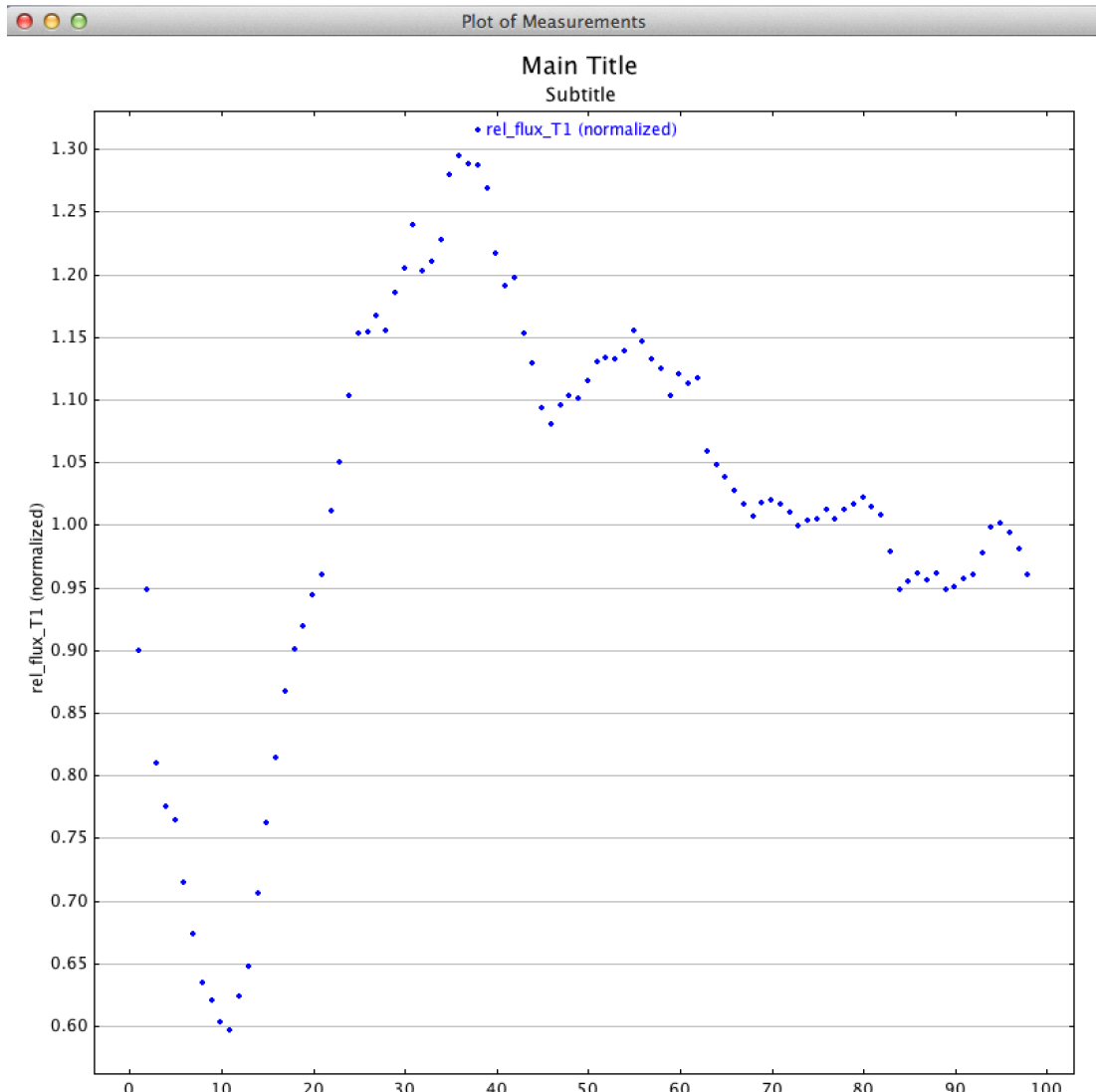
Figure 14: Plot produced by AstroImageJ of a variable target star in a Stack of images.

This is a very preliminary plot but the shape and the extent of the fluctuations are related to the apparent magnitude and gives you an idea of how good your measurements are. Once it has completed the analysis you will want to look at the Measurements table.

Figure 15: Measurements table output after performing multi-aperture photometry.

There is lots and lots and lots of information in this table, well over 100 columns and more if you chose a lot of comparison stars. You should save this output by right clicking anywhere in the table and selecting **Save As**. It will save it in .xls format which is readable by Microsoft Excel or Open Office. You can also save it as a .txt file if you delete the extension and replace it with .txt. Although I don't recommend this since it will be extremely hard to read as a text file. Another option is right clicking and selecting **Copy** and then pasting the table contents into a text editor or spreadsheet program.

For this analysis, only a few columns are really relevant. Those are JD_UTC, Source_AMag_T1, and Source_AMag_Err_T1 columns which correspond to the Julian Date of the observation which was read from the FITS Header, the Apparent Magnitude of Target 1, and the error in the Apparent Magnitude of Target 1. In a spreadsheet it is easy enough to copy those three columns into a separate spreadsheet or text document and then use your favorite plotting software to plot the lightcurve! It's easy to see which images were ruined due to clouds but even with a cloudy night, we were able to obtain good data and produce a lightcurve with an average error of about 0.02 magnitudes.
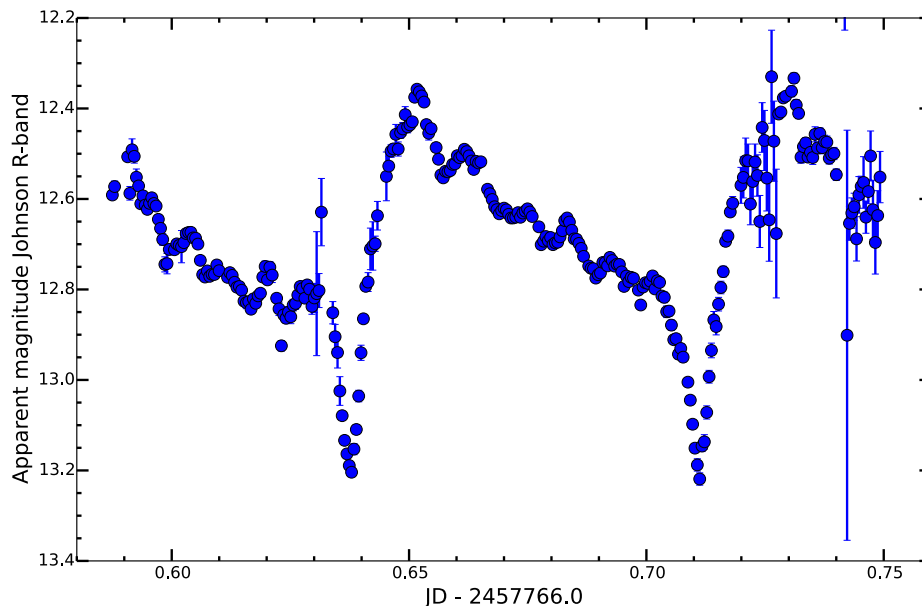

Figure 16: Final lightcurve of HT Cas after reduction and AstroImageJ analysis.