FRI Astronomy Lab #7

Goal: In this lab, you will carefully reduce data from the *Kepler* space telescope using the *PyKE* software package. The nature of these observations demand different considerations than the ground based photometry that you have reduced before. You will perform Fourier analysis on your final light curve to determine the pulsation period of a variable star discovered serendipitously in the *Kepler* data.

Instructions

1. The Kepler mission is a space-based telescope that recorded images of a star field nearly continuously from 2009 to 2013 (for more information, visit `www.nasa.gov/kepler`). The primary goal of this space observatory is to discover and characterize planets by detecting the dimming of starlight during planet transits. Since time-series photometry over a long period of time is the type of data that we use to understand pulsating stars through Fourier analysis, these data are also useful for asteroseismology. (Note: after failure of one of its reaction wheels needed for fine guiding, Kepler is just beginning a new "K2" mission that will monitor new pulsators in different fields for stretches of $\sim$80 days at a time.)

   Visit `http://archive.stsci.edu/kepler/data_search/search.php` and search for the object with "Kepler ID" 3448787. You should see data recorded over $\sim$4 years from "Quarters" 1 to 17. Click on each "Dataset Name" and view the light curve previews. Click and drag your cursor over part of the light curve to zoom in and investigate that portion in more detail.

   Q: For each quarter of data, do you visually see any evidence of periodic pulses? (Write all answers to these questions down and submit them to Canvas with your final plots.)

   Between each quarter of data, the telescope is pointed toward Earth to beam down the data and then repositioned on the star field. Ideally, the data associated with a specific Kepler ID represents the light from the same target star, although measured on a different part of the CCD.

   Q: How might the light curve characteristics change so much between quarters?

2. In order to bust this mystery wide open, you'll need to look at the pixel-level data rather than the "pipeline" reductions. One particularly illuminating quarter of data is Q2. Create a directory for your reductions and download the "target pixel file" from the Q2 "preview" page and `gunzip` it there.

3. This `.fits` file contains the set of images obtained every 30 minutes for this target throughout the quarter. You will be using the *PyKE* software package to understand and reduce these data properly. You may need to reference the documentation for the *PyKE* tasks throughout this lab at `http://keplergo.arc.nasa.gov/PyKE.shtml`

PyKE is a package for *PyRAF*, which is a tool that combines the elegance of *Python* with the power of *IRAF*. Getting these tools to run will require a bit of black magic trickery. Open a terminal window and `cd` to your home directory (~). Copy the file `/usr/local/fri/ureka_fri.tar` to your home directory and untar it. Now type `./clean_shell` followed by `source ur_setup_fri` to gain access to the required scripts. All of the work on this lab will have to be completed in this terminal window.

Now `cd` to your reduction directory. Since *PyRAF* uses *IRAF*, you will need to type `mkiraf` to create a login.cl file, setting your terminal type as "xterm". Begin *PyRAF* by typing `pyraf` and load the *PyKE* package by typing `kepler` (this may take a short while).

4. In order to understand what is going on in these data, you will first look at pixel-by-pixel light curves for the images using the *PyKE* task "keppixseries". Type `epar keppixseries` to open the parameter editor (*PyKE* tasks are *IRAF* tasks, so use epar to define parameters; the *Python* wrapper provides the GUI). You will need to run this task three times, once for each setting of plot type: local, global, and full. Set the infile to the name of the file you downloaded. Set the outfile and plotfile parameters to something sensible that reflects the current plottype. Hit "execute" to run the task. Note that the pixels with grey backgrounds represent the aperture used for the pipeline reductions.

   Q: By inspection of the output, what is the difference between the way that "local," "global," and "full" plots are created?

   Q: Based on these plots, what can you understand about the nature of the intermittent periodic pulses that appeared in the pipeline light curves?

   Q: What can explain the longer timescale changes in the light-level of individual pixels over the course of the quarter of observations?

5. As an asteroseismologist, you are interested in studying the stellar pulsations captured in the images. Use the *PyKE* task `kepmask` to define a custom aperture that captures only the light from the pixels that show pulsations. Focus your cursor on the kepmask GUI and press the "x" key with the cursor over a pixel to toggle inclusion/exclusion of that pixel in the aperture. (We prefer using the "bone" colormap so that pixels included in the aperture are colored green.) Press "dump" to output your custom aperture to a file before closing the window.

6. Use the task `kepextract` to extract a new light curve from the raw pixel data using your custom-defined aperture mask file.

7. Use the task `kepdraw` to plot the resulting light curve. Click the magnifying glass icon and then click and drag on areas of the plot window to examine the light curve in closer detail. The "home" button will return the plot to the default zoom level. **Note:** If your plot comes up blank then you need to include additional pixels using `kepmask` in step 5.

Q: What features do you recognize in the pulsation pattern? Roughly, what periodicities are present? What frequencies do these correspond to? Are there features in the light curve that look "unphysical"?

8. Because of practical constraints on how data is acquired with the *Kepler* satellite, the data is not able to be calibrated with flat fields, accurate sky background measurements, or large apertures.

   Q: Without flat fielding, what effect would the target starlight drifting amongst pixels of different quantum efficiencies have on a light curve?

   In order to remove systematic instrumental effects due to spacecraft pointing and possible glitches, *Kepler* monitors many stars that should be of constant brightness and determines many common trends that are present in the light curves. The resulting set of trends are available for download at `http://archive.stsci.edu/kepler/cbv.html`

   Download the cotrending basis vectors (CBVs) for Q2 to your reduction directory. This file contains the 16 light curve trends detected during Q2 from most common to least common. The *PyKE* task `kepcotrend` finds the best fit of a subset of these CBVs to the data. However, since you are working with a variable star, you need to make sure that you do not "overfit" the data.

   Run the `kepcotrend` task using vectors "1 2" to use only the first two. The top pannel of the resulting figure shows the original data and the CBVs best fit, and the bottom panel shows the new light curve with that trend removed. Use the zoom feature to investigate your results closely. Are all of the systematics taken care of with two CBVs? If not, try again with "1 2 3" to use three trends (you may need to enable the "clobber" option in the parameter editor to rerun the task). Continue in this fashion until the systematics are all gone, but don't use more CBVs than necessary. Save a screenshot (disk icon) of the plots with the best CBV fit at an appropriate zoom level.

   Q: How many CBVs did you have to fit to get the best light curve?

9. Congratulations! You have properly reduced *Kepler* data and recovered a useful light curve of a pulsating star that was serendipitously observed near the intended target. This variable is an RR Lyrae star. RR Lyrae stars are important to identify since they can be used to determine distance scales in the Galaxy. All RR Lyrae stars have roughly the same absolute luminosities, and since brightness decreases with distance-squared, a measure of how bright they appear to us allows us to calculate how far away they are. You can read about the inital discovery of this object at `http://keplerlightcurves.blogspot.com/2012/07/planet-hunters-unlisted-rr-lyrae-star.html`

   Furthermore, this RR Lyrae exhibits Blazhko modulations: a poorly understood phemonenon of long-period pulsation amplitude variations. Since the next step in this lab takes a few minutes to run, read a bit about RR Lyrae stars and the Blazhko effect while the calculations are being made at `http://www.univie.ac.at/tops/blazhko/Background.html`

10. Your final task is to perform Fourier analysis on this star. Open the parameter editor for the `kepft` task to generate a Fourier transform from the outfile created by your best CBV fit. You must set the *fcol* parameter to "CBVSAP_FLUX" in order for the Fourier transform to analyze the fully reduced light curve. Choose sensible minimum and maximum periods that encompass the approximate periodicities that you determined in Step 7. I found that 500 steps in frequency strikes a nice balance between plot quality and computation time. Save an image of the plot window that opens when the calculation completes.

    Q: Using the zoom tool on the plot, what appears to be the frequency of the radial pulsations in this star? What is the period? If you see other peaks in your plot, where did they come from? *(Don't worry about trying to find the frequency of the Blazhko modulations.)*

11. Type `.exit` in the terminal to quit *PyRAF*. Print the images of your best CBV fit and your Fourier transform and turn them in with the answers to the lab questions.

12. Bask, baby…