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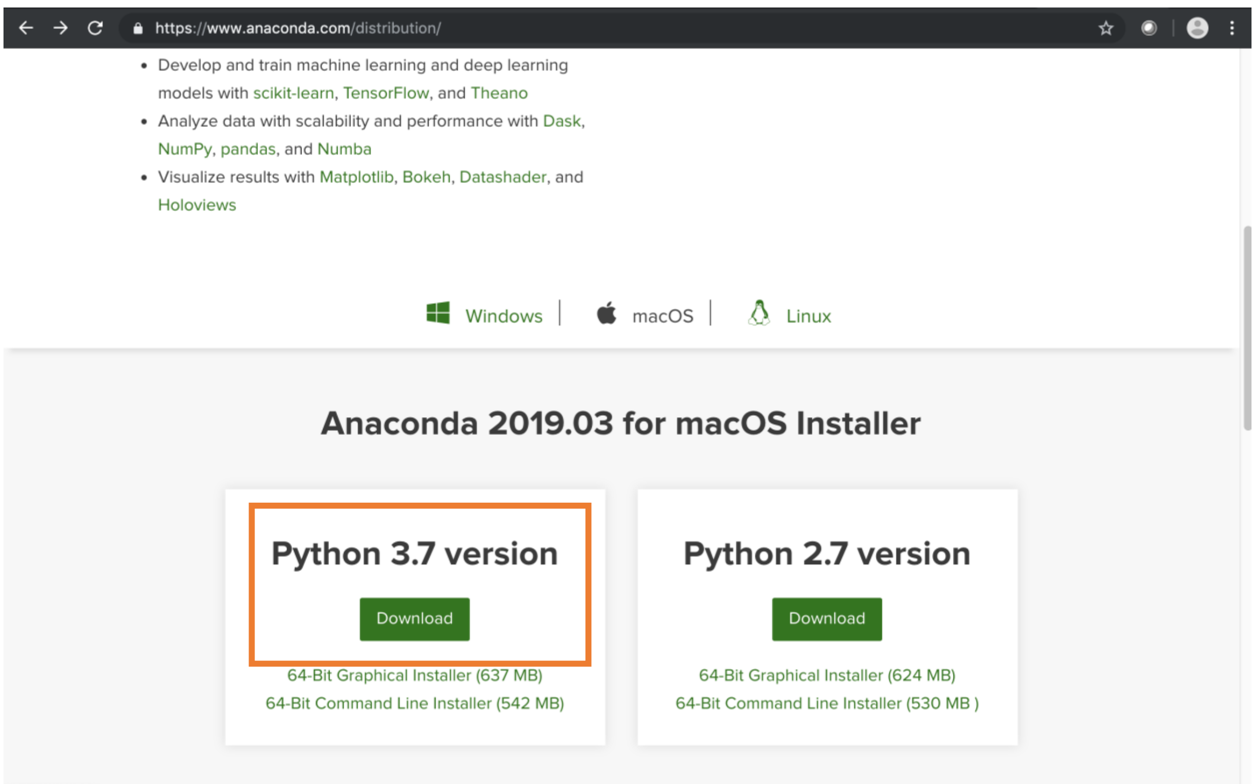
EXOplanet Transit Interpretation Code (EXOTIC) Instructions

Steps I-IV need only be completed once

I. Installing Python using Anaconda

- Installing Python using Anaconda comes with most of the packages you will need to run the Reduction Pipeline
  - Astropy, Scipy, Numpy, Matplotlib etc.
- Link to the installation guide: [Anaconda Download]
- Click on the Anaconda installer (orange box) for macOS and be sure to download the Python 3.7 version.



- Open the downloaded installer and follow the instructions.
- After you have installed Python 3 using Anaconda, test your installation by typing “conda list” into your terminal window and hit enter
  - For instructions on how to open terminal, see section III “Opening the Terminal”

II. Downloading DS9 (Image Viewing Software)

This software will allow you to view the ".FITS" images

- Link: DS9 Download Page
  - Be sure to download the version that corresponds to your operating system version
- Run the installer once it's been downloaded
- Follow the instructions laid out in the installer to finish the installation process
- Here is the User Guide: DS9 User Guide on their website
- To open a fits image with DS9, simply right click on the image in Finder, and select "Open With" and choose "SAOImageDS9"
- When opening for the first time, the system will say the application is by an unidentified developer. To get past this, open System Preferences and under the General pane of the Security & Privacy tab, you can allow the application under "Allow apps downloaded from:"

III. Using the Terminal (skip this step if you are already familiar with the Terminal)

- Opening the Terminal
  - The Terminal app is in the Utilities folder in Applications. To open it, press Command - spacebar to launch Spotlight and type "Terminal," then double-click the search result. Spotlight can also be launched by clicking on the magnifying glass icon in the far right of the system menu bar.
  - You'll see a small window with a white background open on your desktop. In the title bar are your username and the word "bash".
- Changing Directories
  - A "directory" is just another term for a folder in your computer
  - To enter a directory in terminal, type "cd" followed by a space, and then the path to your directory, and then hitting return which will execute the command
    - The path to the folder you want to change into can be found by right clicking on the folder in Finder, and then holding down the option key, and then selecting "Copy 'Your file' as Pathname"
    - Pasting that copied file path after the "cd" is the easiest way to accurately and reliably change into your desired directory
  - To go back to your "Home" directory, simply type "cd" and then hit enter
  - "pwd" can be used to determine your current directory
- Listing Files in a Directory
  - To list all of the files in your current directory, enter "ls"
  - This is a good way to make sure that a/e file you are looking for is actually in the directory you think it is
- Keyboard Interrupt
  - To kill a process or program while its running, hit "Ctrl + c"
- Quitting the Terminal

    - To quit the terminal, after you have killed any processes that were running using the keyboard interrupt, type exit and hit enter
    - It is at this point you can simply close the terminal window by clicking on the red button in the top left corner of the window

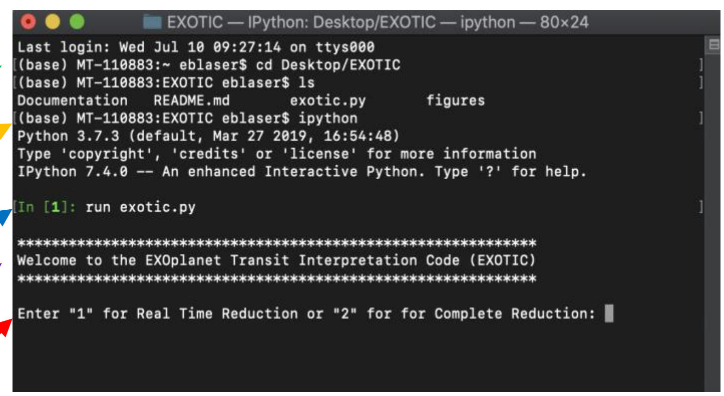
IV. Installing Photutils and PYMC3 Packages

- You can install photutils with conda (recommended) by entering into the terminal:
  `conda install -c astropy photutils`

- You can install pymc3 with conda (recommended) by entering into the terminal:
  `conda install -c conda-forge pymc3`
    - After starting to build the packages, it will ask you if you want to continue and then type "y" and hit enter
- Certain pymc3 plots require ArviZ so to install it, enter:
  `conda install -c conda-forge arviz`
- An online package is used for Barycentric Julian Day conversions so to install it, enter:
  `pip install barycorrpy`
- Restart the terminal by closing the current window, and then opening a new one.

V. Getting the Code to Run

After installing Python and DS9,

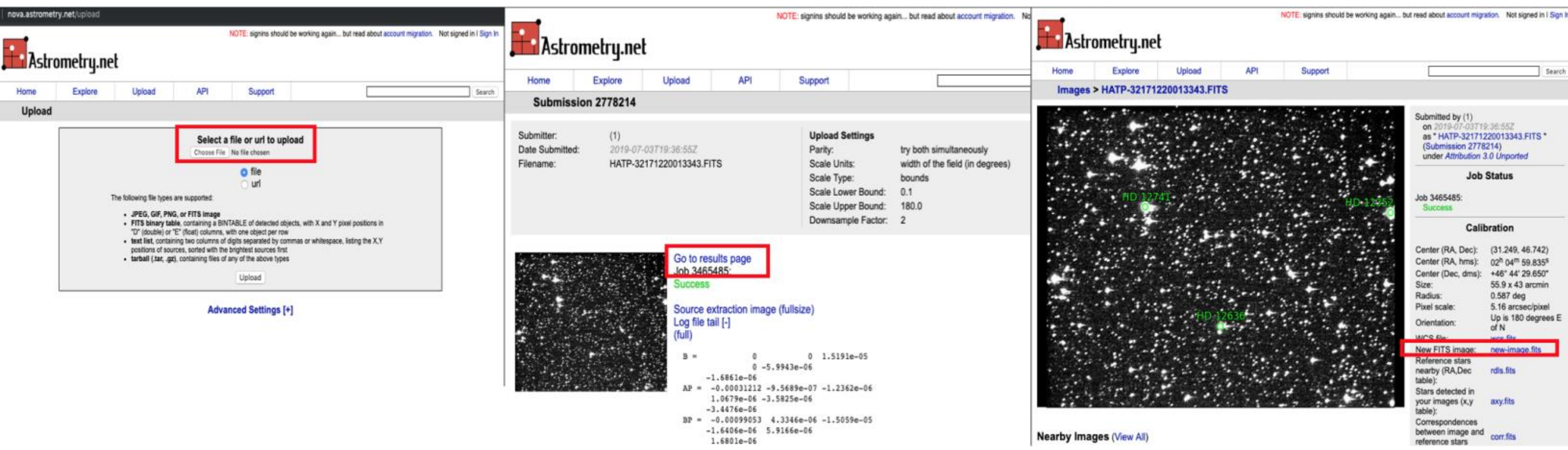


1. Change into the directory in which "exotic.py" is located using Terminal
2. Then run ipython by typing "ipython" and hitting enter
3. Type "run exotic.py" and then hit enter
4. If you see this message, the pipeline is running!
5. You will first be presented with 2 options:
    - Enter '1' to Reduce your Data in Real Time
        - This option should only be selected if you want to a quick reduction your data while you are on an observing run
        - This will simply serve as a visual tool, but will not fit a model lightcurve, nor will it extract planetary data
    - Enter '2' to do a Complete Reduction
        - The default option that should be selected at all times except for the case described in 1ai.
        - This performs a full reduction on all of your data
            - See How it Works for an explanation of the reduction process

VI. Real Time Reduction Routine (skip this if you entered "2")

Now that you have the pipeline running, this chapter will walk you through how to reduce your dataset in real time. The photos used below are using an example data set of HAT-P-32b.

1. Enter the directory path to the FITS Image Files
    a. You will need to enter the complete path to the folder where the images you will be taking will get saved into
        i. If you don't have a folder in which your images will get saved, you will need to make one by simply creating a new folder using finder
    b. The easiest way to get the path to your folder is by right clicking on the folder in Finder, and then holding down the option key, selecting "Copy 'Your file' as Pathname", and then pasting that into the terminal
2. Enter the name of the planet you are observing
    a. For plot title only
3. Start Your Observing Run
    a. Once you start your observing run, ".FITS" files should be entering the directory at the rate you set your observing cadence to.
4. Type "continue" after the first image has been taken and saved after the prompt
5. Entering the Pixel Coordinates of your Target Star
    a. Go to: http://nova.astrometry.net/upload
    b. Upload the first ".FITS" image in your in your dataset to Astrometry.net (left)
    c. After it finishes analyzing your image click "Go to results page" (center)
    d. Then click to download "new-image.fits" (right)



    e. Open "new-image.fits" in DS9, which should now be WCS encoded
    f. Search the SIMBAD database for your target star by typing its name into the search box
        i. Link: [SIMBAD Search Portal]

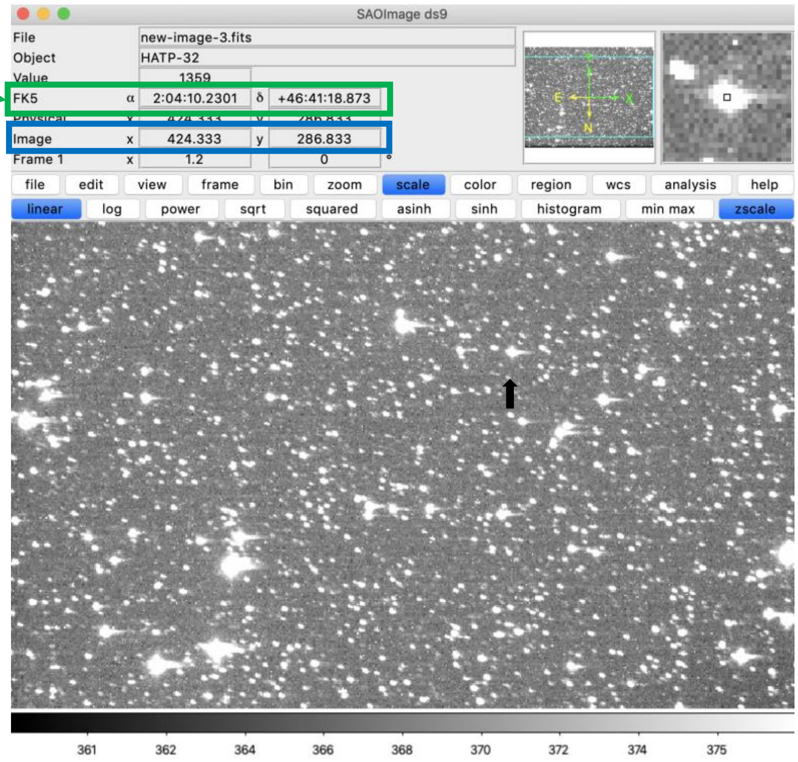
ii. Once you see a page like this one, with your target name, obtain the RA and Dec Coordinates (Green Box) and note the V-mag (Orange Box)

g. Find your target on the "new-image.fits" in DS9 by moving your cursor around on the image until the "fk5" values match the Ra and Dec values shown on the SIMBAD Database

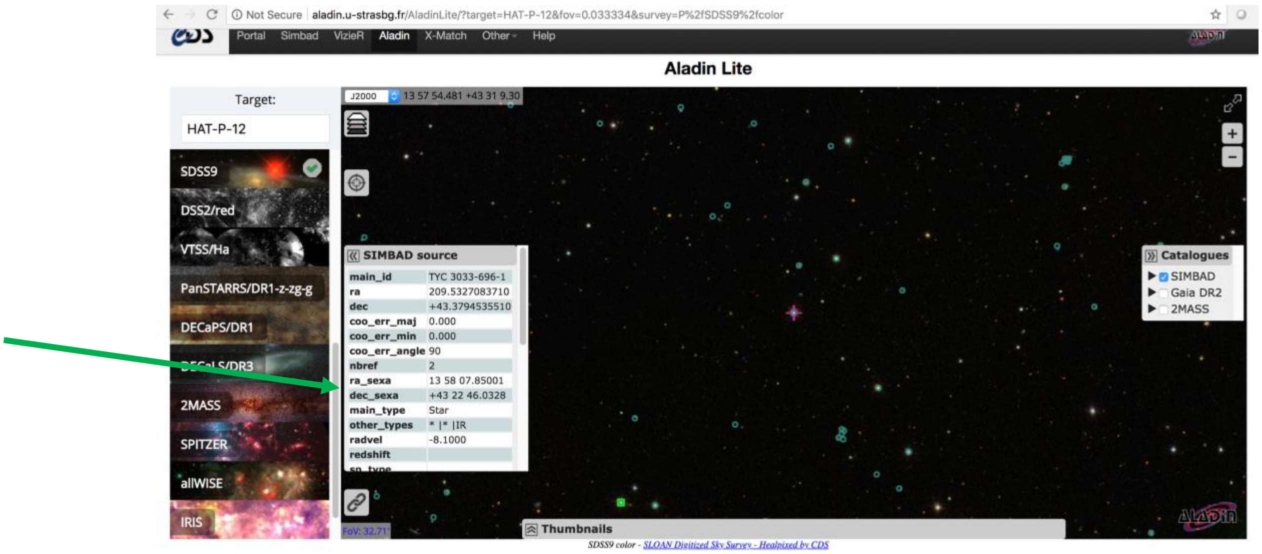
i. You can see stars more clearly by clicking "scale" → "zscale"

h. When the FK5 values match the Ra and Dec from Simbad, the numbers in the boxes next to image (blue box) are the x and y pixel coordinates of your target

Move your cursor around the image (right) until your RA and Dec shown on the green box on the image match the values on SIMBAD



6. Entering the Pixel Coordinates of your Comparison Star
   a. Return to the SIMBAD Page of your Star
   b. Above the image of your target on SIMBAD, click on the “Interactive AladinLite View”
   c. Check the box that says SIMBAD under “Catalogues”
   d. Then click on the nearby stars (green circles) around your target star (purple +), looking for stars of similar brightness
   e. Then in the “SIMBAD source” box on the left, check to make sure you have in fact clicked on a star by ensuring “main_type” = Star
   f. Then scroll down in the “SIMBAD source” box and check the number next to V. If it is close to the V-mag of your target star (within 1.5 units), you have likely found a good comparison star!
   g. Obtain the “ra_sexa” and “dec_sexa” which are located in the “SIMBAD source” box (green arrow)
      i. These are the RA and Dec values for your comp star



h. Find your comparison star on your “new-image.fits” in DS9 using the same procedure you did for finding your target star. (step 4h)

i. Enter the X and Y coordinates of your comparison star into your terminal.

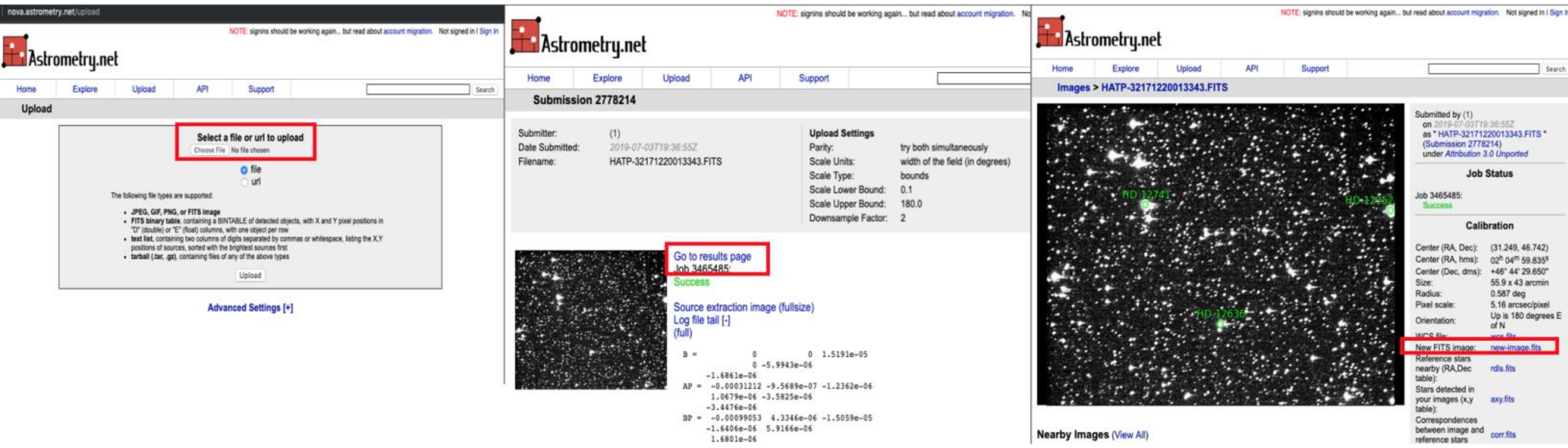
7. A plot of Normalized Flux vs. Time (a lightcurve!) will be generated, and this plot will get updated every time a new image is added to the specified folder.
8. After you are done observing, either close out the plot, or quit the program by typing “Ctrl+c”

VII. Complete Reduction Routine

Now that you have the pipeline running, this chapter will walk you through how to perform a full reduction of your dataset. The photos used below are using an example data set of HAT-P-32b.

1. Enter the directory path to the FITS Image Files
   a. You will need to enter the complete path to the folder where the images you want to reduce are located
   b. The easiest way to get the path to your folder is by right clicking on the folder in Finder, and then holding down the option key, selecting “Copy ‘Your file’ as Pathname”, and then pasting that into the terminal
2. Enter the directory path to the folder you want the results of the reduction saved into
      i. If you don’t already have a folder where you want your plots saved into, you will need to make one by simply creating a new folder using finder in your desired location
3. Enter the name of the planet you are looking at and then the date (MM-DD-YYYY)
   a. This information is just used to make plot titles. It is not relevant to the data reducing itself.
4. Enter the longitude and latitude in degrees of where you observed when prompted
   a. These values are easy to find by simply googling it (an estimate is sufficient)

   b. Don’t forget the signs!
5. Locate Your Target Star
   a. Go to: http://nova.astrometry.net/upload
   b. Upload the first “.FITS” image in your in your dataset to Astrometry.net (left)
   c. After it finishes analyzing your image click “Go to results page” (center)
      i. If the results shown in the figures do not appear, refresh the page.
   d. Then click to download “new-image.fits” (right)



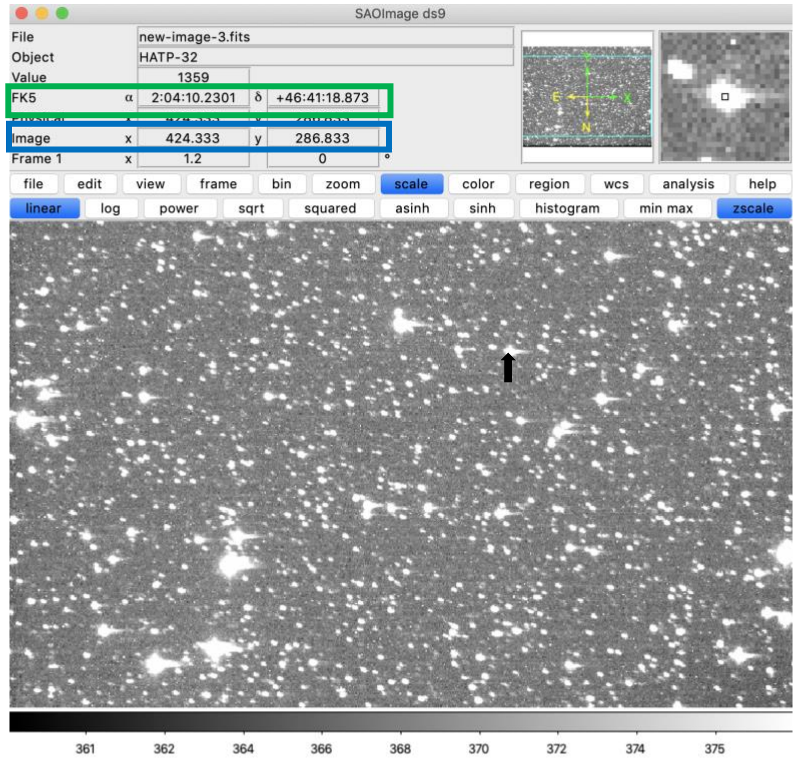
   e. Open “new-image.fits” in DS9, which should now be WCS encoded
      i. One way to check is if the boxes next to the FK5 label in DS9 are no longer empty once you hover your cursor over the image
   f. Search the SIMBAD database for your target star by typing its name into the search box
      i. Link: [SIMBAD Search Portal]
      ii. Use the name formatting from the source tweet

g. Once you see a page like this one, with your target name, obtain the RA and Dec Coordinates (Green Box) and note the V-mag (Orange Box)

h. Enter the Ra and in the form '##:##:##'
   i. For example, in the example above, the Ra should get entered as 02:04:10
i. Enter the Dec in the form '<sign>##:##:##'
   i. For example, the Dec should be entered as +46:41:16 (ignore the values after the decimal)
j. Find your target on the "new-image.fits" in DS9 by moving your cursor around on the image until the "fk5" values match the Ra and Dec values shown on the SIMBAD Database
   i. You can see stars more clearly by clicking "scale" → "zscale"
      1. Blue highlighted buttons in image below

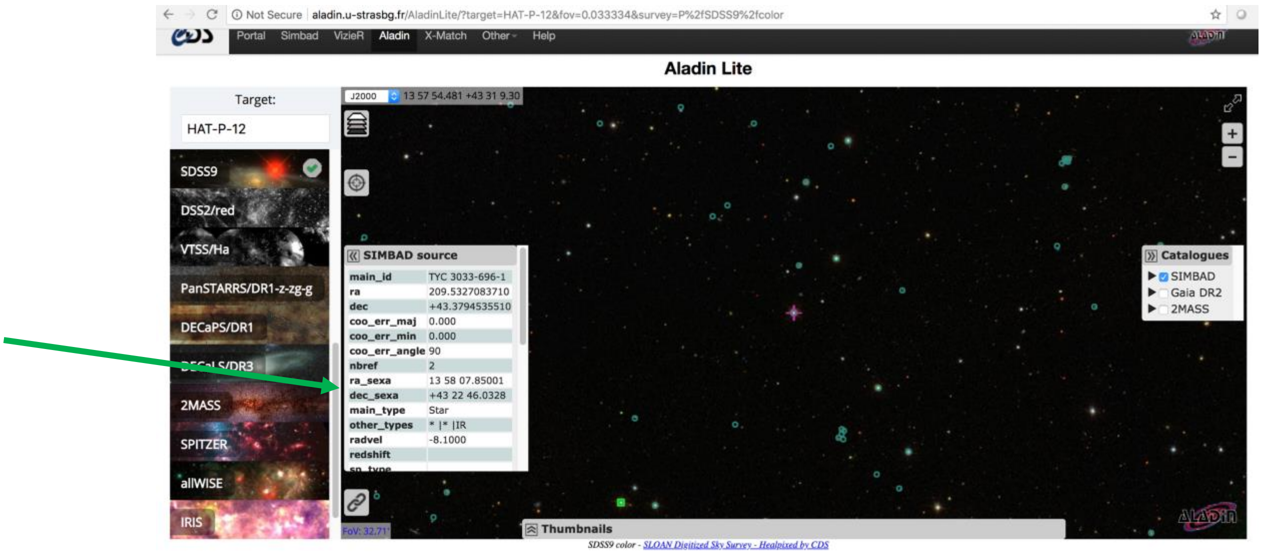
ii. When the FK5 values match the Ra and Dec from Simbad, the numbers in the boxes next to image (blue box) are the x and y pixel coordinates of your target

Move your cursor around the image (right) until your RA and Dec shown on the green box on the image match the values on SIMBAD



k. Enter the Target X and Y Image (pixel) position (Blue Box in image above) into the terminal when prompted

6. Decide how many comparison stars you want to use
   a. 3 is recommended, but any number between 1-10 will do
7. Entering the X and Y Pixel Coordinates of your Comparison Stars
   a. Return to the SIMBAD Page of your Star
   b. Above the image of your target on SIMBAD, click on the “Interactive AladinLite View”
   c. Check the box that says SIMBAD under “Catalogues”
   d. Then click on the nearby stars (green circles) around your target star (purple +), looking for stars of similar brightness
   e. Then in the “SIMBAD source” box on the left, check to make sure you have in fact clicked on a star by ensuring “main_type” = Star
   f. Then scroll down in the “SIMBAD source” box and check the number next to V. If it is close to the V-mag of your target star, you have likely found a good comparison star!
   g. Obtain the “ra_sexa” and “dec_sexa” which are located in the “SIMBAD source” box (green arrow)
      i. These are the RA and Dec values for your comp star



- h. Find your comparison star on your "new-image.fits" in DS9 using the same procedure you did for finding your target star. (step 4h)
- i. Enter the X and Y coordinates of your comparison star into your terminal.
- j. Repeat steps 5b through 5j until you have entered the coordinates for each of the comparison stars you wanted to use

8. When asked if you have calibration images (flats, darks, or biases), enter 'y' if you have them, otherwise enter 'n'
   - a. If you don't know, or aren't sure what they are, you probably don't have them and should enter 'n' and the code will take you to step 8.
   - b. For each type of calibration image you have, enter the directory path to where each set located when prompted
9. Enter the Planetary Parameters for Lightcurve Fitting
   - a. Go to the NASA Exoplanet Archive look up
     - i. Link: [NASA Exoplanet Archive Search]
   - b. Enter the name of your target star in the search bar under "Host Name" then click on its name once you have found it
     - i. The site is case sensitive so be careful with capitalization
     - ii. It should open a site that looks like the image shown at the bottom of page 11
   - c. The code will iterate through each parameter it needs and will attempt to scrape the values off of the Exoplanet Archive website
   - d. It will then prompt you to verify that each parameter is correct
     - i. Parameters: Orbital Period, Mid-Transit Time, Eccentricity, Ratio of Planet to Stellar Radius, Ratio of Distance to Stellar Radius, Orbital Inclination (all boxed in green in the image below)
     - ii. For Mid-Transit Time, you want to pick the largest value in the column and its corresponding uncertainty (the values after the ±).

iii. For everything else, pick the value highlighted in gold if it's available, and then go to the most recently published non-null value if it's not

e. For each parameter it asks if you agree for, if the value the code obtained is not the same as what you see on the Archive, type 'n', and then enter the correct value when prompted

NASA Exoplanet Archive Links

Planet	Related Overviews				Transit Service
	Confirmed		Kepler Pipeline		
HAT-P-32 b	Planet	Host			HAT-P-32 b Transits

Planet Orbital Properties

Planet	Period (days)	Semi-Major Axis (AU)	Inclination (deg)	Eccentricity	Time of Periastron Passage (days)	Longitude of Periastron (deg)	Date of Orbital Solution	Reference
b	2.15000825±0.00000012	$0.03427^{+0.00040}_{-0.00042}$	88.90±0.40	<0.044	null	null	null	Bonomo et al. 2017
b	2.150010±0.000001	null	88.90±0.40	0.0	null	null	null	Stassun et al. 2017
b	2.1500080	null	$89.33^{+0.58}_{-0.80}$	0	null	null	null	Nortmann et al. 2016
b	$2.15000805^{+0.00000093}_{-0.00000097}$	0.0343±0.0004	88.9±0.4	$0.0072^{+0.0700}_{-0.0064}$	null	$96^{+180.0}_{-11}$	null	Zhao et al. 2014
b	null	null	null	$0.20^{+0.19}_{-0.13}$	null	$58.0^{+28.0}_{-53.0}$	null	Knutson et al. 2014
b	2.1500085±0.0000002	null	$89.12^{+0.61}_{-0.68}$	null	null	null	null	Gibson et al. 2013
b	2.150008±0.000001	0.0343±0.0004	88.9±0.4	0.	null	0	null	Hartman et al. 2011

Planet Parameters

Planet	M sin(i)		Mass		Radius			Density	Equilibrium Temperature	Reference
	(Jupiter Mass)	(Earth Mass)	(Jupiter Mass)	(Earth Mass)	(Solar Radii)	(Jupiter Radii)	(Earth Radii)	(g/cm^3)	(K)	
b	null	null	0.75±0.13	238±41	0.1838±0.0026	1.789±0.025	20.05±0.28	$0.163^{+0.029}_{-0.028}$	null	Bonomo et al. 2017
b	null	null	0.830±0.210	264±67	0.180±0.014	1.75±0.14	19.6±1.6	null	null	Stassun et al. 2017
b	null	null	null	null	null	null	null	null	null	Nortmann et al. 2016
b	null	null	null	null	0.184±0.003	1.789±0.025	20.053±0.280	null	null	Zhao et al. 2014
b	null	null	0.79±0.15	251±48	null	null	null	null	null	Knutson et al. 2014
b	null	null	0.8600±0.1640	273.3±52.1	$0.1845^{+0.0029}_{-0.0028}$	$1.796^{+0.028}_{-0.027}$	$20.13^{+0.31}_{-0.30}$	0.18±0.04	1779±26	Gibson et al. 2013
b	null	null	0.860±0.164	273.322±52.122	0.1839±0.0026	1.789±0.025	20.053±0.280	0.19±0.04	1786±26	Hartman et al. 2011

Planet Transit Properties

Planet	Depth (perc)	Duration (days)	Duration (hours)	Mid-Point (days)	Impact Parameter	Occultation Depth (perc)	Ratio of Distance to Stellar Radius	Ratio of Planet to Stellar Radius	Reference
b	null	null	null	2454420.44645±0.00009	null	null	null	null	Bonomo et al. 2017
b	2.300±0.012	null	null	null	null	null	6.06±0.13	null	Stassun et al. 2017
b	null	null	null	2456185.602987±0.000110	null	null	$6.123^{+0.021}_{-0.054}$	$0.1516376^{+0.0008740}_{-0.0005450}$	Nortmann et al. 2016
b	null	null	null	$2454420.44712^{+0.000092}_{-0.000084}$	null	null	null	null	Zhao et al. 2014
b	null	null	null	null	null	null	null	null	Knutson et al. 2014
b	null	$0.12959^{+0.00059}_{-0.00057}$	$3.1102^{+0.0142}_{-0.0137}$	2454942.898449±0.000077	$0.0930^{+0.0710}_{-0.0650}$	null	$6.091^{+0.036}_{-0.047}$	0.1515±0.0012	Gibson et al. 2013
b	1.8523	0.1295±0.0003	3.1080±0.0072	2454420.44637±0.00009	$0.117^{+0.045}_{-0.047}$	null	$6.05^{+0.03}_{-0.04}$	0.1508±0.0004	Hartman et al. 2011

10. Limb Darkening

a. On the NASA Exoplanet Archive page of your planet, scroll down until you reach the section called “Summary of Stellar Information”

Summary of Stellar Information			
Right Ascension	02h04m10.28s	Declination	+46d41m16.2s
Galactic Longitude (deg)	135.69859	Galactic Latitude (deg)	-14.37298
Parallax (mas)	3.4304647653712994±0.0623970254391056	Distance (pc)	291.50569045176132±5.3022265110304
RA Proper Motion (mas/yr)	-9.8±0.1	Dec Proper Motion (mas/yr)	3.5±0.1
Total Proper Motion (mas/yr)	10.4±0.1	Radial Velocity (km/s)	-23.21±0.26
B-band (mag)	null	K-band (mag)	9.990±0.022
Spectral Type	null	Effective Temperature (K)	6207±88
Surface Gravity ($log_{10}(cm/s^2)$)	4.33±0.01	Luminosity ($log_{10}(L_{sun})$)	null
Radius (R_{sun})	1.19±0.10	Mass (M_{sun})	1.09±0.28
Density (g/cm^3)	0.91±0.06	Age (Gyr)	null
Metallicity (dex)	-0.04	Metallicity Ratio	[Fe/H]
V sin(i) (km/s)	20.7±0.5	S-index	null
log R'HK	null	X-ray activity, log(L_x)	null
Number of Hipparcos Light Curves	0	Number of Photometric non-Hipparcos Light Curves	0
Number of Radial Velocity Time Series	0	Number of Amateur Light Curves	0
Number of Spectra	0	Number of Images	3

b. Similar to how you entered the planetary parameters in step 8, the code will once again ask you to verify that the values it scrapes from the Archive are correct
    i. It will ask for the Effective Temperature (green box), the Metallicity (red), and the Surface Gravity in the log(g) box (yellow)

11. Now that you have entered all the necessary information, the code will then reduce the dataset
12. After the reduction component is done a set of plots are generated and saved into your specified directory
    a. The target star’s raw time varying flux (see How it Works sect…)
        i. Figure name: ‘TargetRawFlux<planet name><date>.png’
    b. The comparison star’s raw time varying flux
        i. Figure name: ‘CompRawFlux<planet name><date>.png’
    c. The Normalized Target Flux as a function of phase
        i. Figure name: ‘NormalizedFluxPhase<planet name><date>.png’
13. The code uses an MCMC to fit a model light curve to your data, fitting for airmass, mid transit time, and planet radius
    a. Warning: this will take some time. Usually around 30 minutes
    b. For explanation, see How it Works: Full Lightcurve Fitting Routine
14. Final Light Curve fitted with a model is generated and saved in your specified directory
    a. Figure name: ‘FinalLightCurve<planet name><date>.pdf’
15. The final planetary parameters of Mid Transit Time and Ratio of Planet to Stellar Radius and their corresponding uncertainties will be displayed in the terminal, and also saved as a ‘.txt’ file in your specified directory
    a. Figure name: ‘FinalParams<planet name><date>.txt’

    b. To learn how to interpret your results, go to “How it Works: Results Interpretation”

16. If you want to save your reduced data into the official AAVSO data format file, type ‘y’ when prompted
    a. Enter your AAVSO Observer ID
        i. If you don’t have an Observer ID, it’s probably because you haven’t created an account, which can be done at: https://www.aavso.org/apps/register/
    b. Enter your exposure length in seconds
        i. This is simply how long you exposed for when you took the data
        ii. It often can be found by opening one of the images in DS9, and then going to File -> Display Header
    c. Enter the binning used on your camera
        i. If you don’t know or are unsure, just type ‘1x1’
    d. The file should now be saved as “AAVSO<target name><date>.txt”