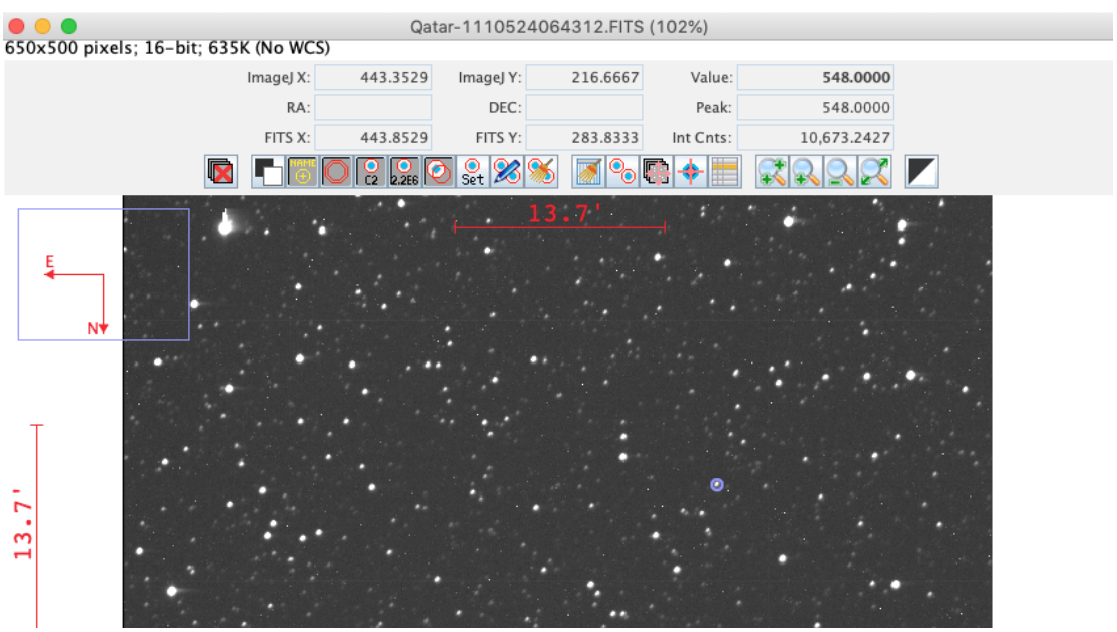
How to Run EXOTIC in the Google Collaboratory Cloud

First, add this folder to your Google drive account (you can do this using Shift-Z to get the “Add Shortcut to Drive” option). Then download the *first* image in the “images” folder to your computer. You might notice that you cannot open it by double-clicking. That is because it is in a special format called .fits. Files in .fits format contain a record of the exact number of photons that hit each pixel in the image during the exposure. For non-astronomical applications, measuring these “ADU counts” precisely is not important, but when you are trying to measure a teensy dip in light from a particular star, as we are doing here, it is critical! In any case, because .fits images do not open by double-clicking, you will need to install an astronomical image-viewing program. I recommend AstroImageJ, but there are many other choices, and you can use whatever works for your system.

The next step is to find the target star. Long ago, astronomers located targets by consulting star charts, and some still do it that way. Others upload images to nova.astrometry.net to “plate-solve” them. After being plate-solved, the coordinates of each pixel will show up in the “RA” and “Dec” fields as you mouse over astrometry.net’s new image in AstroImageJ. You can match those coordinates to the known Right Ascension and Declination of the Qatar-1b host star from the NASA Exoplanet archive (20h13m31.60s+65d09m43.3s), and find the target that way. However, if you study the same starfield for a long time, eventually you will recognize enough of the star patterns (or “asterisms”) in the field that you will neither need star charts nor a plate solution; the target will just pop out at you no matter where it is located in the image.

To simplify the target-finding process for purposes of this example, it is outlined with the blue circle in the image below:



When your mouse is right over the target, the (FitsX, FitsY) coordinates displayed above the image, rounded to ones place, are (444, 284). In addition to the FitsX and FitsY coordinates of the target, you will need the coordinates of a couple of comparison stars, or "comps."

Comp stars

We are looking for *tiny* dips in the light from a host star. If we measure the light that comes from the target directly, we might see fluctuations due to moonlight, clouds, or the atmosphere that would mask the subtle changes we are looking for. This is why we use a comp.

If we pick a comp that is close to the target, then any extra moonlight in the image will affect both the target and the comp equally. Therefore, the light of the target star *relative to* the comparison star will fluctuate only because of the planet passing in front of the target, not because of fluctuations in Earth's atmosphere.

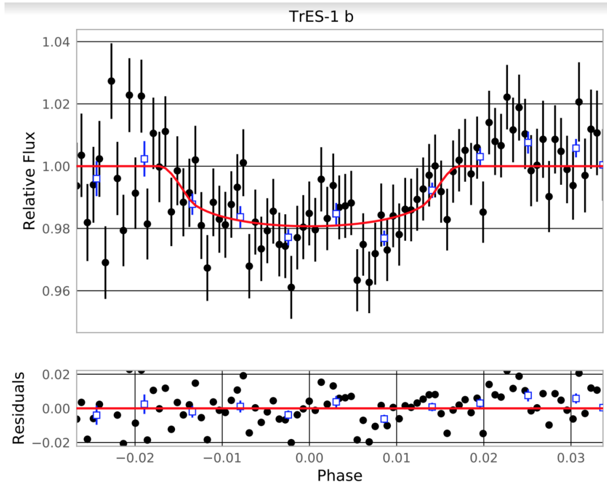
Picking a good comparison star can be tricky. For now, concentrate on finding comps that are 1) close to the target, 2) bright, 3) isolated from other stars (comp stars need to practice social distancing too!). Find the FitsX and FitsY coordinates of each comp by mousing over it the same way you did for the target, and record what you picked in the response template.

Measuring starlight

We could use AstroImageJ to measure the starlight. To do this, we would use double-bullseye tool on the AstroImageJ menu bar to set how big we want our circle (or "aperture") to be, place the aperture on the target and comp in each of the 90-ish images in the folder, record the photon counts (displayed in the "Int Cnts" box above the starfield) for those two stars in each image, and plot their ratio as a function of time to see the dip in starlight. However, you would quickly go cross-eyed trying to record all those numbers. (You definitely *would* memorize the starfield, though. 🙂)

Instead, we'll let the EXOplanet Transit Interpretation Code, or EXOTIC, do that part. EXOTIC has special algorithms for optimizing the size of the aperture, picking the best comp from among the choices you give it, and includes several other features that allow it to measure the starlight in each image very accurately.

EXOTIC asks you to enter the pixel coordinates of your target star and comp(s) in the first image. Then, it looks through all of the other images in the folder, following the target and comp(s) through the series and measuring their light. Finally, it fits a curve to the light it measured. If it is able to follow the target and comps all the way through the series, the curve it generates will look something like this:



EXOTIC will also ask about darks, flats, and biases. You can find the directory of darks in [the folder](), and we do not have flats or biases. Darks are images taken when the camera shutter is open, but the lens cap is on, so light cannot enter. These images are used to minimize the effect of sensor noise through a process called "dark subtraction".

Sometimes the target and / or comps drift out of the field of view of the telescope, and sometimes clouds obscure the image for a little while during the run so that the software cannot fit the curve. If this happens, EXOTIC might give an error or else make a curve that looks less comprehensible. This particular set of Qatar-1b images was chosen so that that will not happen, but for future reference, what you would do in this case is to look through the images and see if you can figure out what might have gone wrong. If there are no obvious clouds or image corruption, try running with a different comp star. Another trick that might be helpful is to remove the first few images in the series, because sometimes it takes the telescope a while to settle down and lock in on the target star. Above all, keep and save all of your notes and document your observations while you are working with any set of images. Once you have found the coordinates of your target and a couple of comps, you are ready to run EXOTIC according to the instructions in red below.

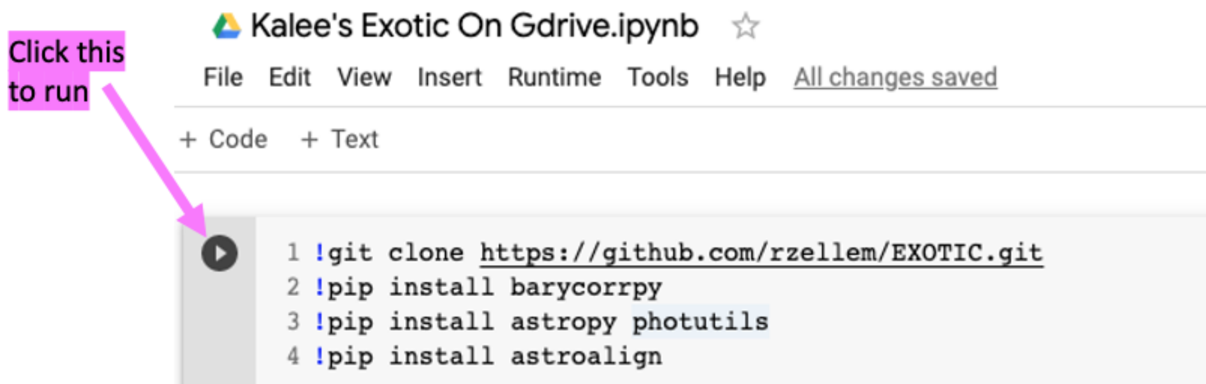
In order to run EXOTIC (or any other code that reads and writes files), you need to give the code permissions to access your Google drive account. This is analogous to the permissions that you implicitly give to any code that you run on your own hard drive. Therefore, you may want to run this using a throwaway Gdrive account. (I have run EXOTIC on my own harddrive and also using my actual Gdrive account without any issues. However, my husband, who is in computer security, insists that I pass along this advice.)

1. Open the Google drive of the account you want to use. Go to this Colaboratory:

https://colab.research.google.com/drive/1px6Z0X1DPMnaUh1kZ2qKyVNZIls13Ti9?usp=sharing

2. Click "File → save a copy in drive" to create an editable copy on your own Google drive account. Title it with your name so that you know it is yours.

3. When you open up your editable copy of the Colaboratory in your Google drive, your "runtime" is automatically assigned to a virtual machine somewhere in the cloud. First, you need to install on that machine some modules that EXOTIC needs in order to run. To do this, run the first code cell by clicking the arrow at the upper left.



(It will spit out a bunch of gobbledygook as it installs stuff, which you can ignore.)

4. Then, you need to "mount" your Google drive onto that virtual machine. Do that by running the second code cell, clicking the link, and copy-pasting the authorization code into the field when prompted.

5. Once your Google drive is mounted, run the third and last code cell to fire up EXOTIC. Note that you will have to specify the location of the .fits files images that you want EXOTIC to process using a path that starts "/content/drive/My Drive/". The folder that will contain the plot output should also start "/content/drive/My Drive/".

For this example, for the first three inputs, you will want to enter 2, 1, 1 (choosing a complete reduction, having it perform aperture photometry on fits files, and inputting via command line):

Enter the directory names as follows, starting with "/content/drive/My Drive/" then the remainder of the path. For example, for the MicroObservatory Qatar-1b transit of 2011-05-24:

```
Enter the Directory Path where FITS Image Files are located:
/content/drive/My Drive/2011-05-24/images

Enter the Directory to Save Plots into:
/content/drive/My Drive/plots
```

(The last command tells EXOTIC to create a directory called "plots" in your top-level Gdrive.)

EXOTIC needs the following data about the observatory where these images were taken, which is the Fred Lawrence Whipple Observatory in Mount Hopkins, Arizona. **NOTE: Do not forget that the longitude needs to be negative!!**

```
planet name                          Qatar-1b
Obs. Latitude (+=N,-=S)              +31.68
Obs. Longitude (+=E,-=W)             -110.88
Obs. Elevation (meters)              2616
Target Star RA (hh:mm:ss)            20:13:32
Target Star Dec (+/-hh:mm:ss)        +65:09:43
Camera Type (CCD or DSLR)            CCD
Pixel Binning                        2x2
Exposure Time (seconds)              60
Filter Name (aavso.org/filters)      CV
Observing Notes                      In collaboration with the Center for
Astrophysics | Harvard & Smithsonian, MicroObservatory Network
```

You can find the other data about Qatar-1b that EXOTIC asks you about on the Qatar-1b NASA Exoplanet Archive page. You don't need to worry about what all these numbers mean (for now), but it is important to make sure that the numbers on the archive match what EXOTIC thinks they should be. EXOTIC should be using the values in the orange-highlighted rows on the Exoplanet Archive page.

We do have flats and darks, so you'll answer those questions as follows:

Flats: no

Darks: yes (specify the directory of darks as above, e.g. "/content/drive/My Drive/2011-05-24/darks")

Biases: no

EXOTIC will take a little less than an hour to run on the Qatar-1b example transit using Google Collaboratory. When it finishes, you'll find the final lightcurve and a bunch of output parameters in the folder where it was told to save the plots. The output parameters will have the following format:

Transit Midpoint

Transit Midpoint Uncertainty

```
FINAL PLANETARY PARAMETERS
The fitted Mid-Transit Time is: 2455489.6647491655 +/- 0.003926 (BJD)
The fitted Ratio of Planet to Stellar Radius is: 0.13099761220008008 +/- 0.010478 (Rp/Rs)
The transit depth uncertainty is: 0.27451859612648777 (%)
The fitted airmass1 is: 0.9133011036108907 +/- 0.006532
The fitted airmass2 is: -0.008738392228978986 +/- 0.005418
The scatter in the residuals of the lightcurve fit is: 0.835%
```

The Transit Midpoint is listed in Barycentric Julian Days, which is the number of days since Julius Caesar died (or killed someone, or did something else important), measured from the center of mass of the solar system. (More on BJD is here if you are interested.) Screenshot your lightcurve and parameters, and insert the images into the response template.

Congratulations! You just reduced your first exoplanet transit!

Having worked through this example, you are ready to try your hand at a new dataset if you wish. I have several datasets hanging around on Google drive that have never been analyzed before. This means that no-one knows whether or not there is a lightcurve buried in the images. If there is, you can measure it and use the measurement to update NASA's ephemeris for the system ("ephemeris" is the prediction of when the next transit is expected to occur). Also, if you reduce several transit midpoint measurements for the same system, it will become possible to do some additional science. Specifically, you could analyze the ensemble of measurements for periodic *variation* in the timing of the transit midpoint, which might be the signature of another, unseen planet in the system.

If you do decide to analyze a new dataset and find that it generates a good lightcurve, it is important to add your measurements to the repository of data used by astronomers to 1) understand the astrophysics of exoplanet systems and 2) optimize telescope time allocation on coming space telescope missions. Therefore, for any *new* datasets that you analyze, you should get into the habit of adding your measurements to the database that is maintained by the American Association of Variable Star Observers. Do ***not*** do this for the sample dataset in this exercise, because that has already been done, and it is important to avoid entering the same dataset twice. However, if you reduce a MicroObservatory exoplanet dataset that has *not* been analyzed before, then you could follow the instructions here to upload it to AAVSO. (If you reduce a dataset that was *not* taken by the MicroObservatory, then you would follow a similar process, but would substitute the corresponding specs for those instruments.)

Another consideration is that your measurements will have more credence if you publish them in a paper that has been vetted by astronomers in the field. I encourage you to both upload and publish and can show you how--please reach out if you are interested (kaleeg@stanford.edu).