ASTR 5110: Fall 2025

Final Project

Time Series Photometry of a Transiting Planet System

Absolute Deadline: 11:59 PM December 16, 2023

During our APO observing run we took, as a group, ARCSAT imaging data in the Sloan g filter for a hot Juptier system TOI-2046 (Kabáth et al. 2022, NASA ADS link to the paper). We observed the TOI-2046 for a complete transit on the night of October 30, 2025. This data enables a new measurements of the hot Jupiter's transit timing.

Hot Jupiters are gas giant planets with masses and radii similar to Jupiter that orbit their host stars in less than 10 days. These planets are valuable targets for studying planetary atmospheres and formation mechanisms due to their short orbital periods and large sizes. TOI-2046b is a particularly interesting hot Jupiter discovered by the TESS space mission. The planet has a mass of $2.30 \pm 0.28\ M_{\rm J}$ and a radius of $1.44 \pm 0.11\ R_{\rm J}$, orbiting an F8V star with a period of 1.497 days. The system is remarkably young, with an estimated age of 100–400 Myr, making it one of the few known young planetary systems hosting a hot Jupiter. Continuous monitoring of TOI-2046b's transits enables precise characterization of its orbital parameters. Transit timing measurements allow testing if this planet is still undergoing orbital evolution. This is particularly interesting for such a young planetary system.

The goal of this project is to

1. Perform relative photometric measurements using the ARCSAT data.
2. Derive a precise and calibrated light curve of TOI-2046.
3. Make a new transit timing measurements.
4. Update the ephemerides of the system.

Along the way, we will investigate a few other aspects of the methods of photometry and apply other concepts we have covered/will cover in this class:

- CCD data reduction and image processing
- aperture photometry
- photometric calibration
- error analysis

You will rely on your own learning from the semester and creativity to figure out how to do some of these required tasks. Your grade will be based partly on (a) how creative and thoughtful you are in undertaking this work, (b) the quality of your final results, and (c) the quality of your write-up. As before, you should endeavor to make your turned in work resemble a short journal-style paper, following standard journal style, including a scientific purpose, procedure (including information about the data and what you did to reduce it), results (with figures, equations and tables derived as necessary) with answers to the questions posed below, and scientific conclusions.

You can work together in teams of no more than three people, but all members of the team must contribute comparably to the work turned in. Teams should turn in a single hard copy and also send me a PDF copy of the assignment. Teams should also turn in a contribution statement (one paragraph per team member).

The teaching staff can act as a resource for questions and advice. Access to the logfile you collectively took will be via UVACanvas (in the "APO Observing Projects" folder). We will let you know how best to access the data files. The python package `photutils` is helpful for conducting the photometry measurements. You may find that the code AstroImageJ can do many useful functions for this assignment.

References

- Kabáth et al. (2022) [link to paper]

Lab Assignment

1. Reduce the Data. In your own group "reduced" directory, reduce copies of all frames according to the procedures outlined in the lectures. You can use the python `ccdproc` package, and you need to explain precisely which steps were done and how, and you need to make sure that any scripts you are using are doing the correct thing and will achieve the quality of reduction you need to succeed.

   Put the final, reduced individual frames, as well as all output photometry files, in a location that we can access for checking results (obviously, give us permissions and whatever else are needed to access these files, as well as any instructions on naming conventions one needs to know to figure out what is what).

   IMPORTANT: Include in your lab write-up clear descriptions of the steps you undertook in the reduction of the images, and tabulate the names and locations of critical calibration frames you used in the process (e.g., combined biases, darks, flatfields). Give key information about what calibration frames you used, and what combination methods you may have adopted (e.g., means, medians, modes, avsigclips) to create these calibration frames and why. Explain if/how you have dealt with spurious pixels, such as hot pixels and cosmic rays.

2. **Image Profiles, Curve of Growth, and Aperture Size Evaluation** Investigate the image profiles across the target data set and establish or argue for their relative stability in terms of seeing and image quality variability, using relevant plots to make your case. Produce curve-of-growth plots (flux vs. aperture radius) as well as S/N vs. aperture radius plots. Justify your choice of aperture and sky annulus sizes.

3. **Derive and Check Instrumental Magnitudes**

Use aperture photometry on the ARCSAT data to measure the instrumental magnitudes within a fixed fraction of the light for TOI-2046 and at least three reference stars that are not saturated, not in danger of falling off the edge of some frames, and that are the closest in brightness to the target source, across all frames in the dataset. For accurate relative photometry, it is critical for the following work that you measure the *same fraction* (which could be "100%"—but justify how you accomplished that) of the starlight for all frames!

For the three reference stars relative to TOI-2046 make a plot showing:

- Instrumental Sloan g magnitude versus (MJD) date+time of observation for the ARCSAT data.

In a separate plot, show for your chosen reference stars (each star with its own distinct symbol and color) the following:

- Instrumental Sloan g magnitude versus airmass (X) for the ARCSAT data of the target field.

Both plots should include uncertainties.

Comment on what you see in these plots. Explain the likely reason for any outliers from the general, expected trend, and how/why/whether you eliminate them from analysis. The results of this analysis may lead you to suspect that some data were taken under non-photometric conditions or have other problems. Carefully describe how you reach any such conclusion and what you choose to do about it. For example, explain how non-photometric data would manifest in the plots.

4. **Bouguer's Law:** Use the your plots and data to verify Bouguer's Law. By linear regression applied to the data for each of your chosen reference stars fit separately, derive the atmospheric extinction coefficient k_g , as defined in the lecture notes, and compare this airmass coefficient against expectations for a filter of this wavelength. Note that you should derive a k value for each reference star (at least three). Tabulate them and their uncertainties. Give the RMS of the residuals to each fit for each reference star. This can be done after removing obvious outliers.

5. **Relative Photometry and Transit:** Combine relative photometry of TOI-2046 with reference stars to create a lightcurve in relative flux vs. MJD. Explain combination methods and treatment of outliers or offsets. Make sure to include uncertainty in the final light curve and explain how the uncertainties are derived.

6. **Derive the transit timing** Locate the eclipses and derive the eclipse mid-time of all eclipses in the data. You may want to use the "bisected chord method" (e.g., Section 5 of `https://britastro.org/vss/Handbook15b.pdf`) to determine the time of the observed mid-eclipse. You can also find the eclipse mid time by fitting an eclipse profile model (e.g., `https://lkreidberg.github.io/batman/docs/html/index.html`). Please provide the uncertainties of the eclipse timing.

7. **Compare the observed transit timing with the published results**

   (a) Analysis 1: Use the published orbital parameters to predict the transiting timing and compare it with your observed value? Are they consistent? In this comparison, pay close attention to uncertainty estimates and use them to establish your reasoning.

   (b) Analysis 2: Use the published orbital parameters as priors. Perform a transit profile fit using a Bayesian method. Compare and discuss the prior and posterior distributions of the orbital period.