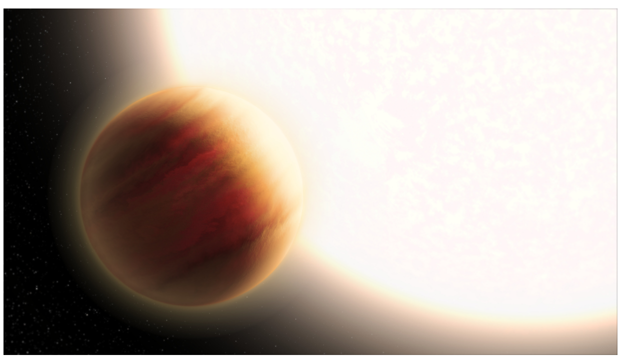
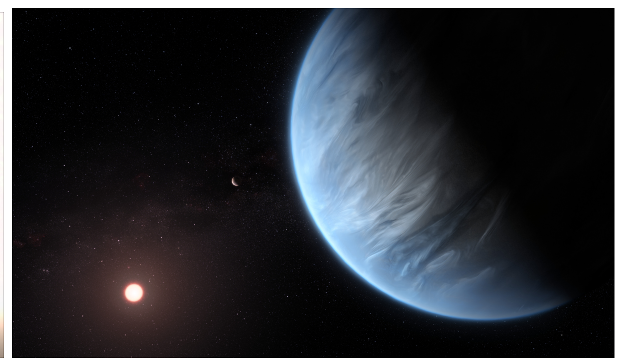
Exoplanet Transits
Introductory Guide

Background

Extrasolar planets (exoplanets for short), are planets that orbit stars other than our Sun. Astronomers believe that most stars in the universe host exoplanets, meaning that most stars in the night sky contain their own unique solar system of one or more planets. Compared to the planets of our solar system (Earth, Mars, Jupiter, Saturn, etc.), however, exoplanets can be quite different. For example, many of the first exoplanets detected were "hot Jupiters" - planets the size and mass of Jupiter but orbiting much closer to their host star than even Mercury in our own solar system. We've also detected planets much more massive than Jupiter orbiting at huge distances, far beyond the orbits of Neptune and Pluto, and super Earths, rocky planets many times more massive than Earth that would have crushing gravity at their surfaces. These are just a few of the strange worlds discovered so far.

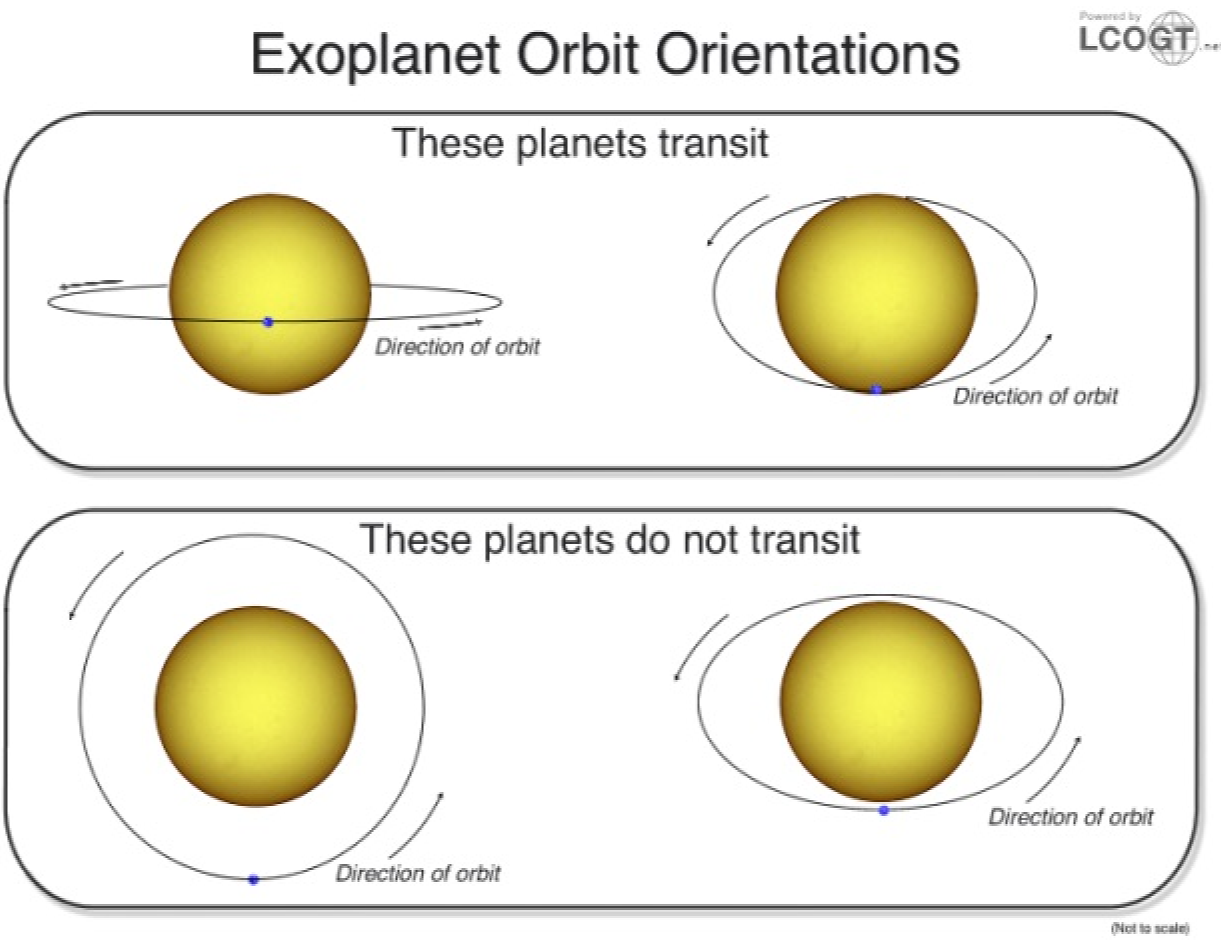



Conceptual artist illustrations of two different exoplanet systems, the first being the hot Jupiter 51 Pegasi b.

Despite exoplanets being extremely common, not a single exoplanet was confidently known until the 1990s. This is because exoplanets can be very difficult to detect. The essential reason is because exoplanets often do not emit any of their own light in the visible portion of the electromagnetic spectrum and so they are far dimmer than stars. The visible light from exoplanets is actually just light from the host star reflected off the surface. To give an example of how much dimmer planets are than stars, in the visible wavelengths that our eyes can see, Earth is 500 million times fainter than the Sun. Even Jupiter is 100 million times fainter. To make matters worse, when exoplanets are viewed from the extreme distances of interstellar space (lightyears away), exoplanets appear very, very close to their host star. If Earth was orbiting the star Alpha Centauri (one of the closest stars to our solar system), it would appear less than one arcsecond away from the star from our solar system. One arcsecond is 1/3600 of a degree. For some perspective, that is less than the width of a dime viewed 2.5 miles away. All together, trying to take pictures of exoplanets is extremely challenging. A frequent comparison of the difficulty is trying to see a firefly buzzing around a lighthouse a few miles away.

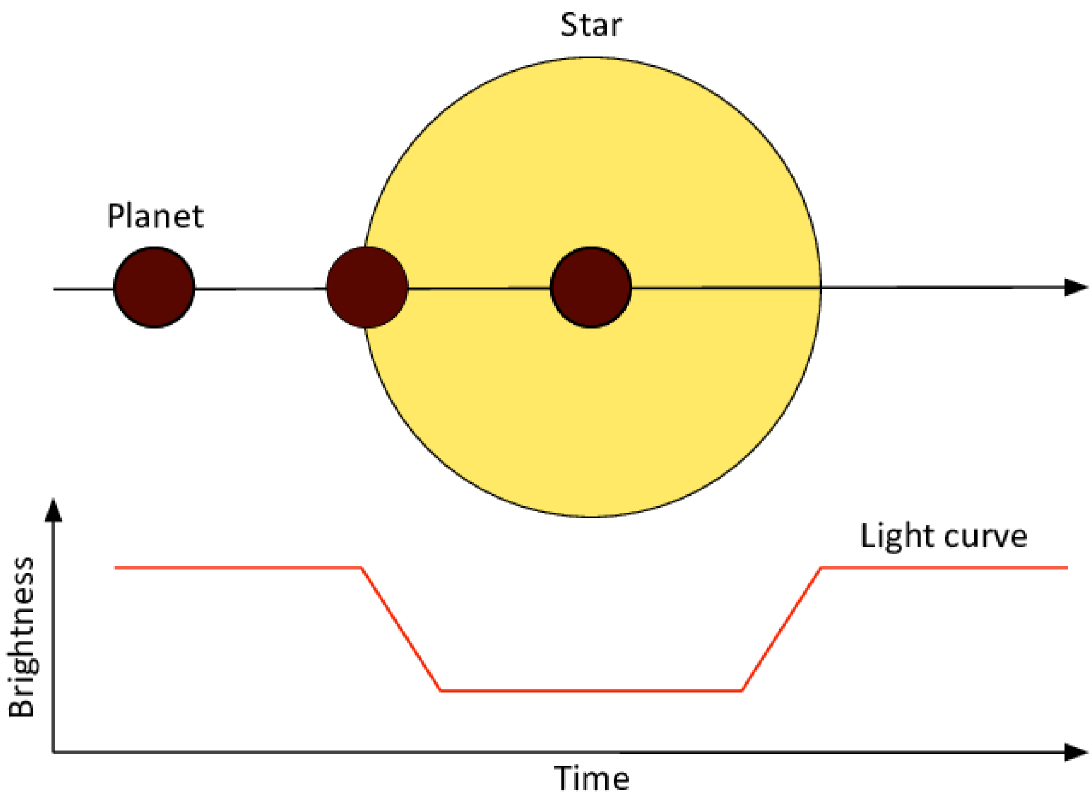
Thankfully, astronomers have come up with a number of techniques to overcome the fundamental problems presented by exoplanets and to detect them successfully. In this project, you will be using the most successful of these methods - **the transit method**.

The transit method detects exoplanets by looking for the light that an exoplanet blocks rather than the light it emits or reflects. If an exoplanet is orbiting in just the right orientation as viewed from Earth, it will pass in front of its host star and partially eclipse some of the star's light. The process is quite similar to the more familiar phenomena of the moon eclipsing the sun, but happening at a much smaller scale and much farther away. How much light is blocked depends on both the size of the planet and the size of the star, but it can be as much as a few percent of the star's total light. While still small, that is far more favorable to detect than the millions of times less light that planets reflect compared to their stars. The downside is that the vast majority of exoplanets do not have orbits with orientations that produce transits.



Orbits can be oriented in any plane in space. If the plane of an exoplanet's orbit is not in the line of sight of the Earth, the exoplanet will not transit and therefore will not be detectable by the transit method.

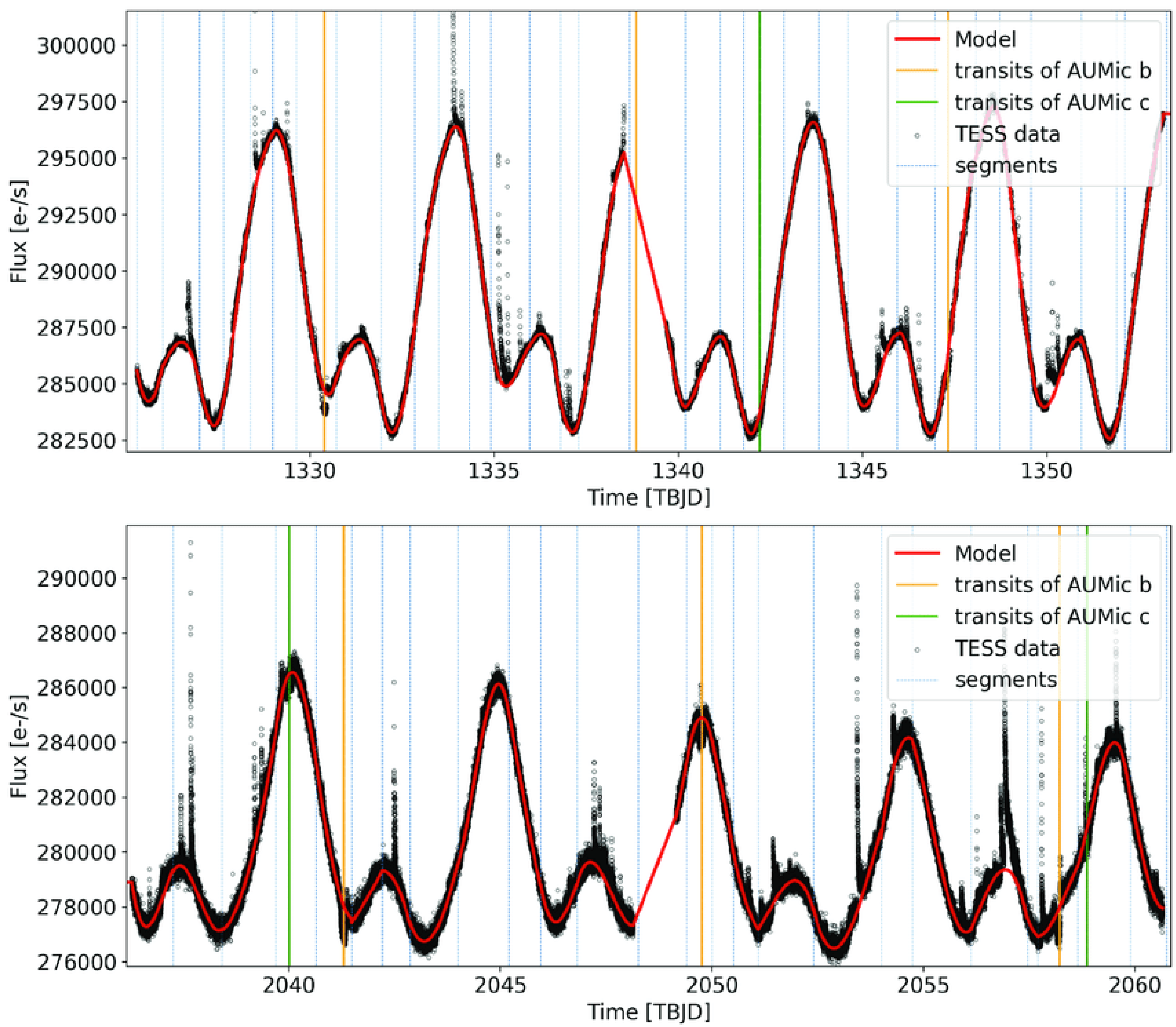
Let's look at the anatomy of what is known as a transit lightcurve. A lightcurve is a sequence of measurements of stars brightness over time. Measuring the brightness of a star is called photometry, so a lightcurve is a sequence of photometric measurements over time. It could be over one night, or potentially over many months if measured by a space telescope. The hallmark of transit is that the star's brightness will go from being relatively constant to experiencing a sudden dip over the duration of the transit then go back to being the same constant level as before. The time when the lightcurve is initially dimming is known as the transit ingress and corresponds to the time when the planet first begins to block star light but is not fully within the area of the star. Once the planet is fully contained within the area of the star it is in-transit and the lightcurve will once again maintain a relatively constant brightness, but dimmer than the un-eclipsed star. The transit egress is when the lightcurve begins to brighten again and is when the planet is leaving the area of the star.



Anatomy of an exoplanet transit. The brightness dips as the planet begins crossing in front of the star before reaching a constant depth when the planet is fully contained within the area of the star.

As with all things, detecting a transit isn't always as easy as it may sound. The problem that is typically encountered is that a star's lightcurve is rarely constant, even without any transiting planets. Many stars are volatile and can flare or have other periodic variations in brightness that can be larger than the signals from planets. Often the observing conditions on Earth like passing clouds or a turbulent atmosphere can create signals that look like or mask exoplanet transits. It's also possible that a star could be a binary star, and what looks like a transit from a planet is actually a partial eclipse from a second star. Finally, there is an inherent limit to how precisely we can measure a star's lightcurve. If a transit is small enough, it can be completely lost within the random noise of measurement errors.

Because of the number of ways a false signal can be mistaken for an exoplanet transit, astronomers have to do strict vetting to confirm a transiting planet. One of the first requirements is that a transiting planet has to be seen to transit multiple times with a regular interval. If a transit is seen 3 times with the same time between each transit, it removes most sources of false signals as possibilities. After that, astronomers will look for signs of a binary star to confirm that the signal is from a planet and not just another previously undetected star.

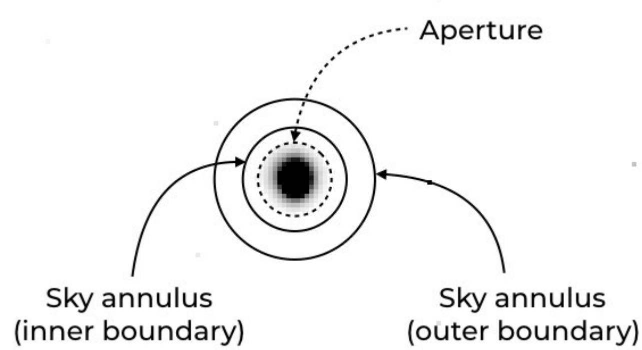


Example of highly variable lightcurves with flares and periodic features that can hide exoplanet transits. Despite the difficult nature of this lightcurve, two exoplanet transits have been successfully detected.

How Photometry is Calculated

As previously mentioned, measuring the brightness of a star in an image is called photometry. To measure the brightness of a star in an image, we need to add up the signal from the star in all the pixels that we know contain light from the star. For our transit photometry, we do this by using **aperture photometry**. An aperture is just a circular area we will center on the star in the image. Within the aperture, all the pixel counts will be summed together to give us a measure of the total light that came from the star. The important decision for this kind of photometry is how big an aperture we should have. In general, you want your aperture to be large enough to collect something like >90% of the light from the star, but not much larger, otherwise we will start including noise from the image background.

In addition to the aperture that will measure the light from the star, we will also include an annulus. An annulus is just two concentric circles where we will measure all the light between their two radii. The purpose of the annulus is to measure how much light is in the background of the image and not coming from the star. This way, we can subtract the background level of light from our aperture to isolate just the star light and not include any background. It will also allow us to measure the typical noise in the background of our image.



Questions to Answer:

- Why are exoplanets so difficult to detect?
- Do exoplanets need to be similar to the planets in our solar system?
- Why is it that only some exoplanets produce transits?
- What two factors determine the depth of an exoplanet transit?
- What is a lightcurve?
- How can we confirm that a dip in a lightcurve is from an exoplanet and not from some other source?
- How does noise interfere with the detection of a transit?
- What is an aperture and annulus? How are they used to compute photometry?

Data for your project

The dataset will be a lightcurve taken by the Nickel 1-m telescope at Lick Observatory (just outside of San Jose, CA). This data was taken by the workshop instructors on June 19, 2022. The lightcurve is an observation of the known transiting exoplanet Wasp-2 b spanning ~3 hours. The lightcurve includes about 30 minutes of the star's lightcurve before ingress and 30 minutes after egress so the entire transit is visible. Exoplanets named Wasp were discovered by a search program called the Wide Angle Search for Planets. Wasp-2 b was discovered by this program in 2007.

Goals for Project:

- Convert a sequence of science images into a photometric lightcurve
    - Understand how photometry is calculated
    - Understand why comparison stars are useful
- Fit a transit model to data to extract a duration and depth
- Convert depth to a planet radius to learn something about the planet
- Estimate the smallest transiting planet that could be detected in data of the given quality