Investigating Signs of Orbital Decay in an Exoplanetary System

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Background

Exoplanets are planets that orbit a star other than our own. The first confirmed exoplanet was discovered using the radial velocity method, which measures the "wobble" of the star as it is gravitationally affected by the orbiting planet (Wolszczan A.; et al. 1992). More recently, an additional detection method has been developed that is even more effective than the radial velocity method. This method is called the transit method.

The transit method utilizes a star's decrease in brightness when an orbiting planet passes between the star and the observer.

When a planet transits, its brightness decreases during its passage across its host star. Once the planet moves off the star, the star's brightness returns to its previous level. The star's brightness during the transit can be shown on a plot called a light curve (Figure 1). The transit begins at the ingress and ends at the egress.

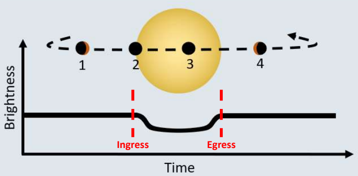


Figure 1: A depiction of an exoplanet at various points in its orbit around its star. The light curve is a plot of the star's brightness over time, which is dependent on the exoplanet's position in its orbit.

TrES- 1b

Discovered in 2004, TrES-1b was the first of five exoplanets found by the Trans-atlantic Exoplanet Survey (Alonso, R; et al. 2004). TrES-1b is the primary target for my research because it is suspected to be experiencing orbital decay. It is a Jupiter-like gas giant orbiting an orange dwarf star slightly cooler than the Sun. TrES-1b has a transit duration of approximately 3 hours and orbits its star every 3.03 days.

Equipment

My observations were conducted using the UNH Observatory on the Durham campus. The telescope used is a Celestron C-14 Schmidt-Cassegrain with an f/11 focal ratio. I imaged the transits using an SBIG STXL 6303e CCD camera. A CCD camera converts incoming photons to an electrical current proportional to the number and energy of photons it receives.

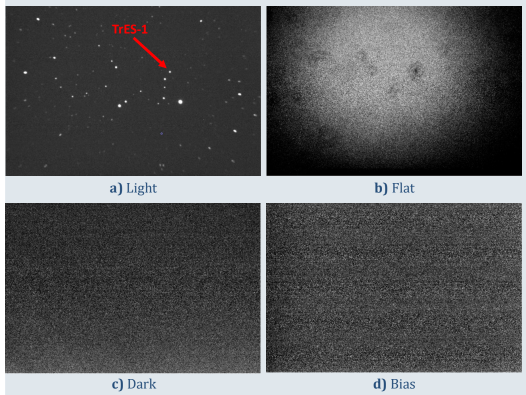
Orbital Decay

A planet in an unstable orbit around its star may begin to experience orbital decay and migrate toward the host star, thus decreasing the orbital period. This will affect the timing of observed transits and they will occur slightly more frequently. Other processes such as apsidal precession or the presence of other planets in the system can also create orbital instabilities. Thus, many transits must be observed over a sufficiently long period of time such that these effects can be measured. TrES-1b is a system believed to be experiencing orbital decay due to a suspected decreasing orbital period, but more data is required to determine a trend over a longer period of time.

Imaging Transits

Find a clear night with an observable transit → Locate target star with telescope → Image transit with CCD camera → Calibrate images → Perform photometry on calibrated images

Figure 3: This flowchart shows the general process I performed to capture images of a transit and analyze the data.



a) Light
b) Flat
c) Dark
d) Bias

There are many factors that can affect the quality of transit images (figure 2a), including improper camera exposure time, imperfect telescope focus, cloud cover, moonlight, and pixel to pixel variation on the camera's sensor.

Photometry is the process of converting an object's brightness to numerical values. I performed photometry on my images using the software AstroImageJ (AIJ), which is the same software utilized for analysis of NASA's data for the Transiting Exoplanet Survey Satellite (TESS). AIJ performs photometry and produces the light curve plots for data analysis of the transit.

Photometry can be performed on raw transit images, though the quality of the light curve is much better when the images have been calibrated.

Figure 2: Figure 2a is the starfield of TrES-1b taken by a CCD camera, whose pixels translate incoming photons into an electrical current. Figures 2b-d are three types of calibration images that are used in image processing to improve the quality of the images for photometry.

Light Curves

My light curves were produced in AIJ which performs the necessary photometry on the images as well as imports the calibration images to process the data. To produce the best possible light curve, it is necessary to take images of the transiting system before and after the expected transit ideally for 30-60 minutes. This allows for a baseline measurement of the star's brightness out of transit to be taken so that the software can determine how much of a decrease in brightness occurred. Reference stars are selected to provide a comparison against the host star's brightness change. The reference stars must be chosen carefully as they must not be variable themselves. Many stars in the sky are variable and it is important to select stars whose brightness does not vary over time.

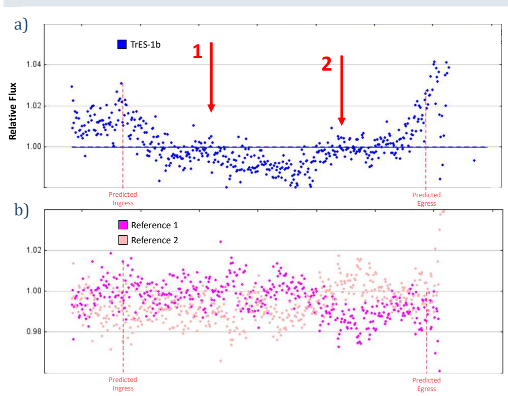


Figure 3: Figure 3a is the light curve of the star's brightness over time. Figure 3b is the plot of two reference stars that were used as a baseline to determine the relative brightness of the transiting star.

Figure 3a shows a light curve for a TrES-1b transit I captured on March 5th, 2022. While there is an obvious period of decreased brightness, it is visible that this plot is inconsistent with what is expected for a light curve. The first marked location on the plot shows the curve plateauing before continuing to decrease. The second marked location shows another flattening of the curve before it continues to increase again. This trend indicates that the data is adversely affected by local sky conditions as mentioned above. Ideally, transit data is best collected from space-based platforms – above Earth's atmosphere. The UNH Observatory is located only 20m above sea level which often leads to instability of sky conditions. It should be noted that just before egress, the Sun was beginning to brighten the sky, and this resulted in the unusual upward trend on the light curve. Due to the brightening sky, the software was unable to produce a high-quality light curve to this data.

The variability of the reference stars in the plot illustrates the low quality of local sky conditions during this transit observation. This type of local sky conditions is common for New England.

Discussion

An accurate and reliable light curve is crucial to studying possible orbital decay in an exoplanetary system. The center of the transit can be determined from the light curve and is used when creating plots to study orbital decay. The transit center can be identified even from a partial transit where either the ingress or the egress is missing, though having both yields a more accurate value of the transit center. I was unable to identify a transit center from the data I took at the observatory. The largest factors for this were cloud cover, sunlight interference, and nonoptimal telescope tracking. There are methods that can be applied to the telescope's software to enable better tracking of the target, which should improve the quality of the data as the star will drift less across the image throughout the duration of the transit.

It is important to have reliable orbital decay plots because they help us to better understand what mechanisms are at play in exoplanetary systems. Studying other solar systems in different phases of their evolution can help us learn about solar system formation and dynamics over time.

Future Plans

I will be performing a deeper analysis of the TrES-1b system using data that other observers have submitted to the Exoplanet Transit Database (ETD). This contains several years of transits submitted by other astronomers, and with this extra data I will be able to apply several fit lines to the data including a decay curve and an apsidal precession curve. I will be analyzing the Bayesian Information Criterion (BIC) for each model to determine if the orbital decay model best describes the data or if there is another cause for apparent decay, such as apsidal precession. I also plan to extend my research to include the Wasp-10 system once I have further analyzed the TrES-1 system. I plan to employ a new tracking method with the telescope's software to improve the quality of my transit images so that they can provide more reliable light curves.

References

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