Exoplanet Transits

At RFO

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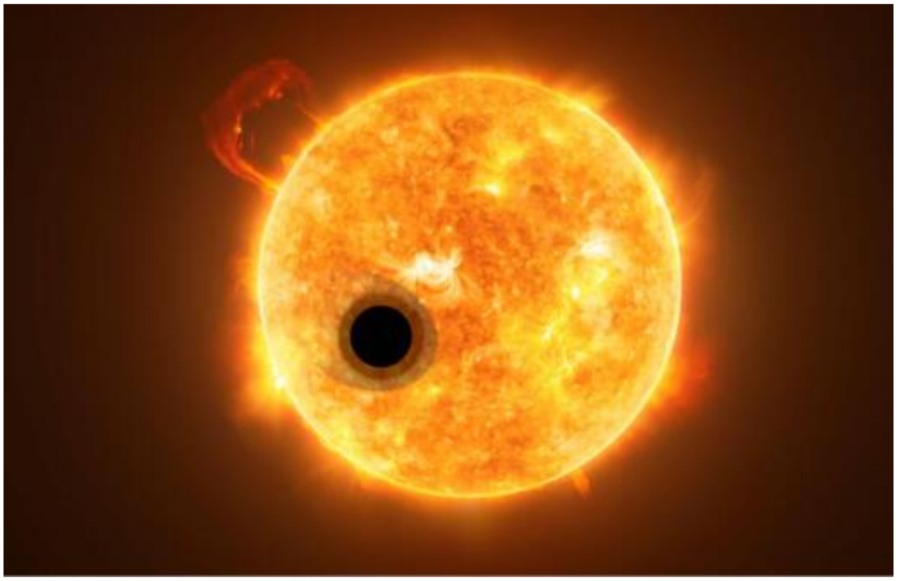
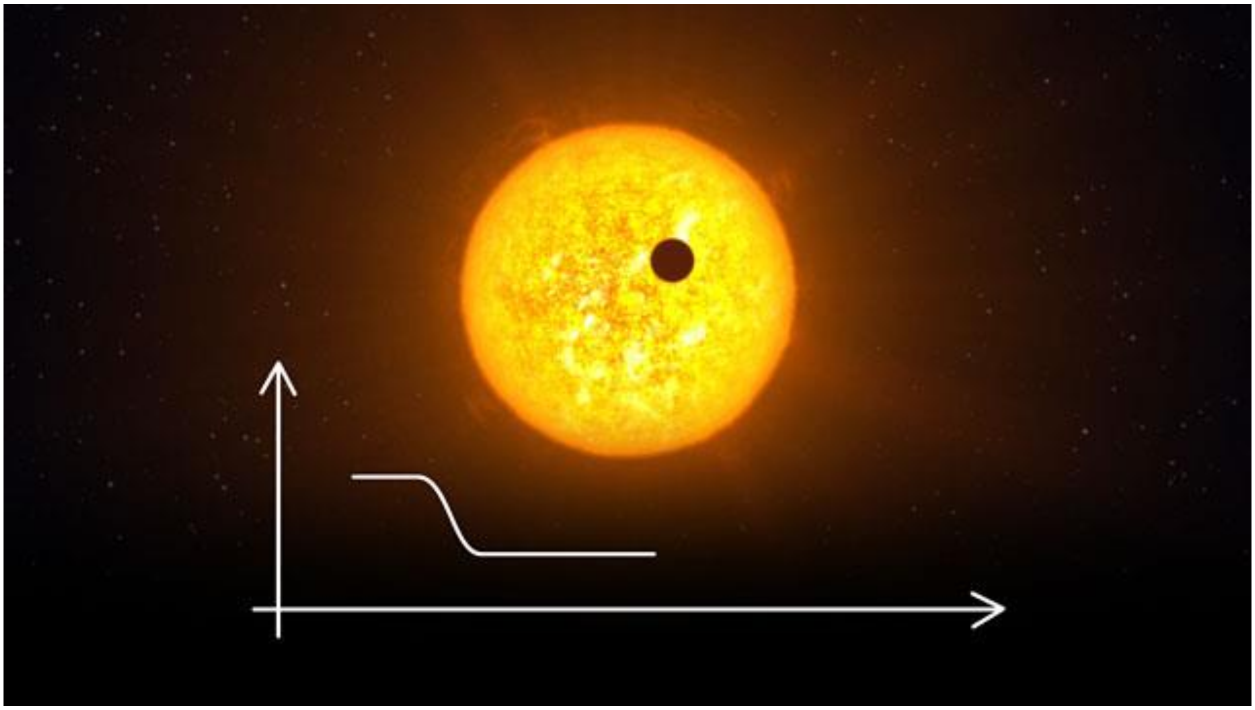
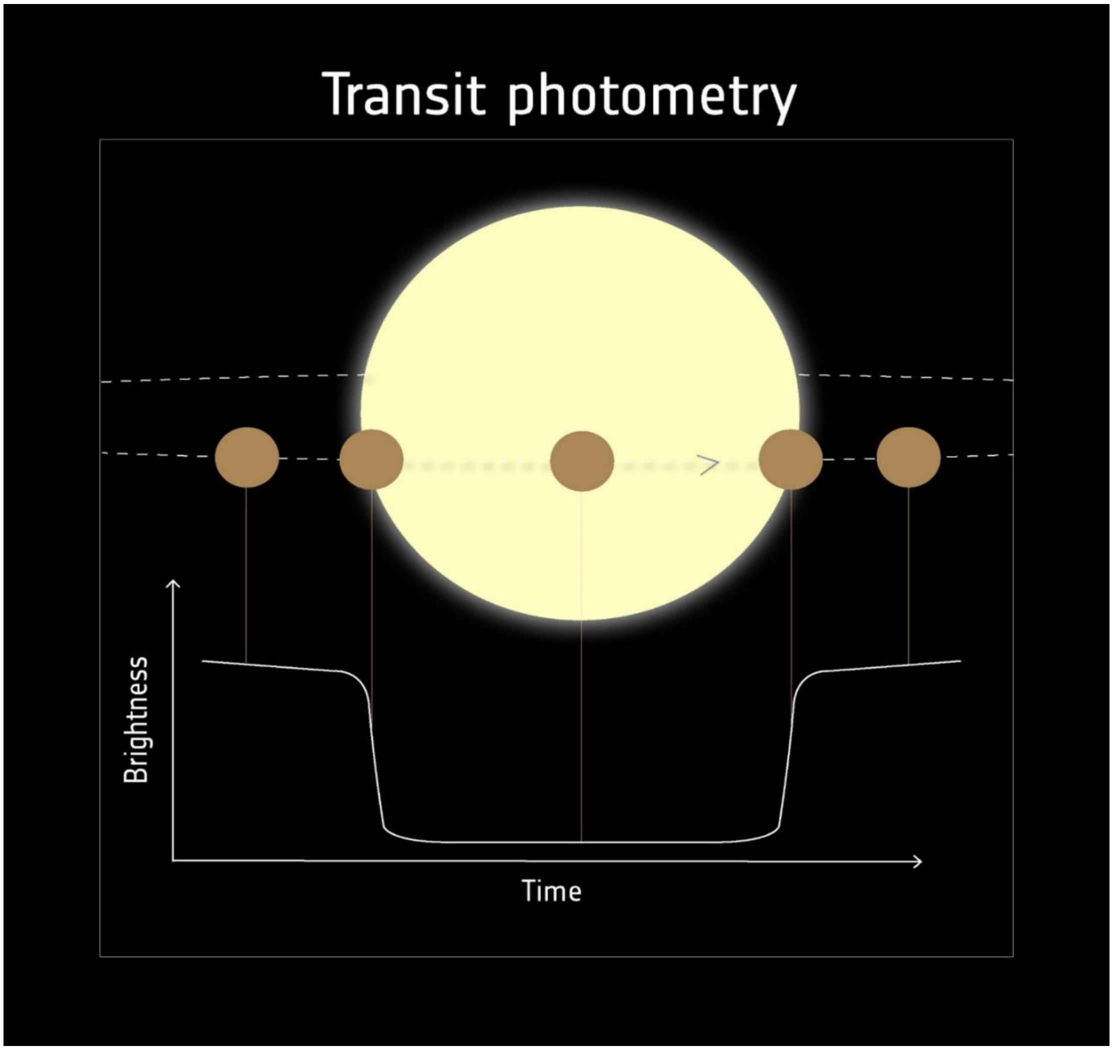


What is it?

An **exoplanet transit** is the passage of an exoplanet across the disk of its star. If the orbital plane of the exoplanet is oriented close to our line of sight here on the earth, we can detect these events. The planet will block some of the light from the star and we can detect a decrease in brightness.



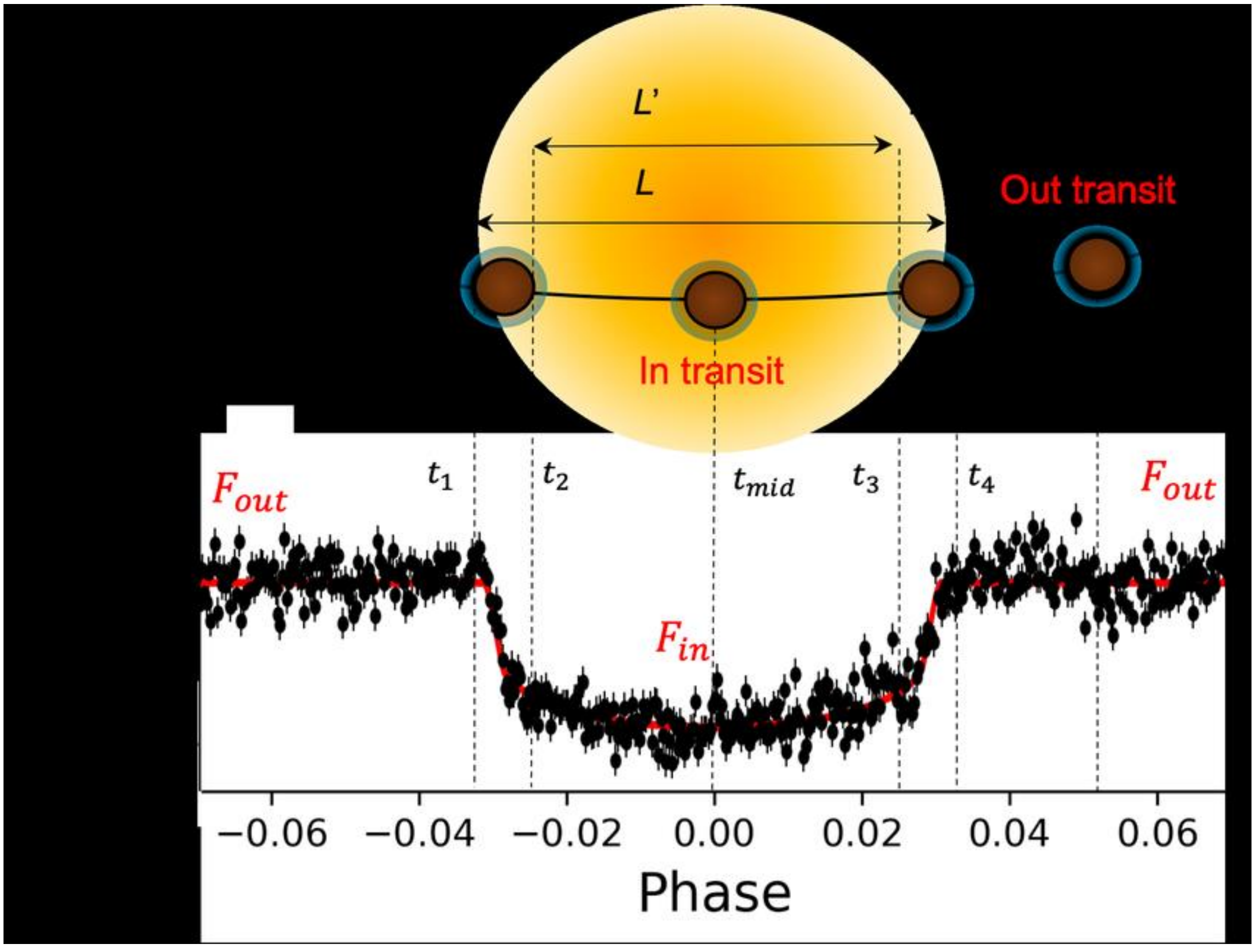
The plot on this illustration indicates a schematic light curve for such an event. The light curve indicates the effect on the brightness being measured for the star.



This is the view we would see if we could actually see the planet as it crosses the disk of the star. The resulting light curve for the measurement of the brightness of the star during this event is known as a transit curve. The planet is transiting across the disk of the star. There is a specific relationship between a point on the transit curve and the position the planet will have on the disk of the star. When the planet begins to pass across the disk of the star the observed brightness will decrease. This phase is known as the ingress of the transit. The increase in brightness is when the planet is leaving the disk. This is known as the egress of the transit. As the planet passes across the disk the brightness will remain relatively constant. The depth of this curve can be used to determine the relative size of the planet.

This transit curve represented here is the "textbook" representation of an exoplanet transit.

Actual transit curves can often depart from this simplified representation. And the individual measurements will include statistical fluctuations and measurement errors.



As indicated here, the planet can have an extended atmosphere which can cause the ingress and egress to appear more gradual. Real stars do not have uniform brightness across their disk and exhibit limb darkening. The center of the disk is brightest with a slow decrease toward the limb. This will cause the bottom of the transit curve to be non-uniform with the deepest region at the center of the transit and slowly sloping upward toward ingress and egress. Real planets have different physical characteristics which will be reflected in their transit curves. Stars can have surfaces which can be very different from what we observe on our sun.

Phase is the fraction of the time between the middle of one transit and the next transit. This is the fraction of the orbital period of the planet. The time t_1 is the time that the edge of the planet would appear to first touch the limb of the star. The time t_2 is the time the entire disk of the planet has moved to cover a fraction of the surface of the star. The time t_3 is when the planet has just reached the opposite limb. The time t_4 is when the planet has left the surface of the star. The time t_{mid} is the middle of the transit event. F_{out} is the brightness outside transit, and F_{in} is the brightness during the transit event.

There are now more than 5000 known or suspected planetary systems, many of which have known transit events. Most extrasolar planets are discovered by detecting transits while monitoring the brightness of stars. Stars discovered to have planets typically have names according to the catalogs in which they appear. However, stars with planets are usually given designations based on the project which led to their discovery as having planets. Examples include HATP, WASP, KELT, Kepler, or TESS. Transits were observed at RFO in April 2024 for the objects HATP-20, XO-7, and XO-1.

There are several resources for predictions of transit events. These include the NASA Exoplanet Archive, which includes a major database for all information related to exoplanets. In particular, this archive includes the **Transit and Ephemeris Service**, which provides predictions for all known transiting planets. Other resources include the **Exoplanet Transit Database (ETD)** maintained by the Czech Astronomical Society, and the **Transit Finder (TAPIR)** maintained by Swarthmore College.

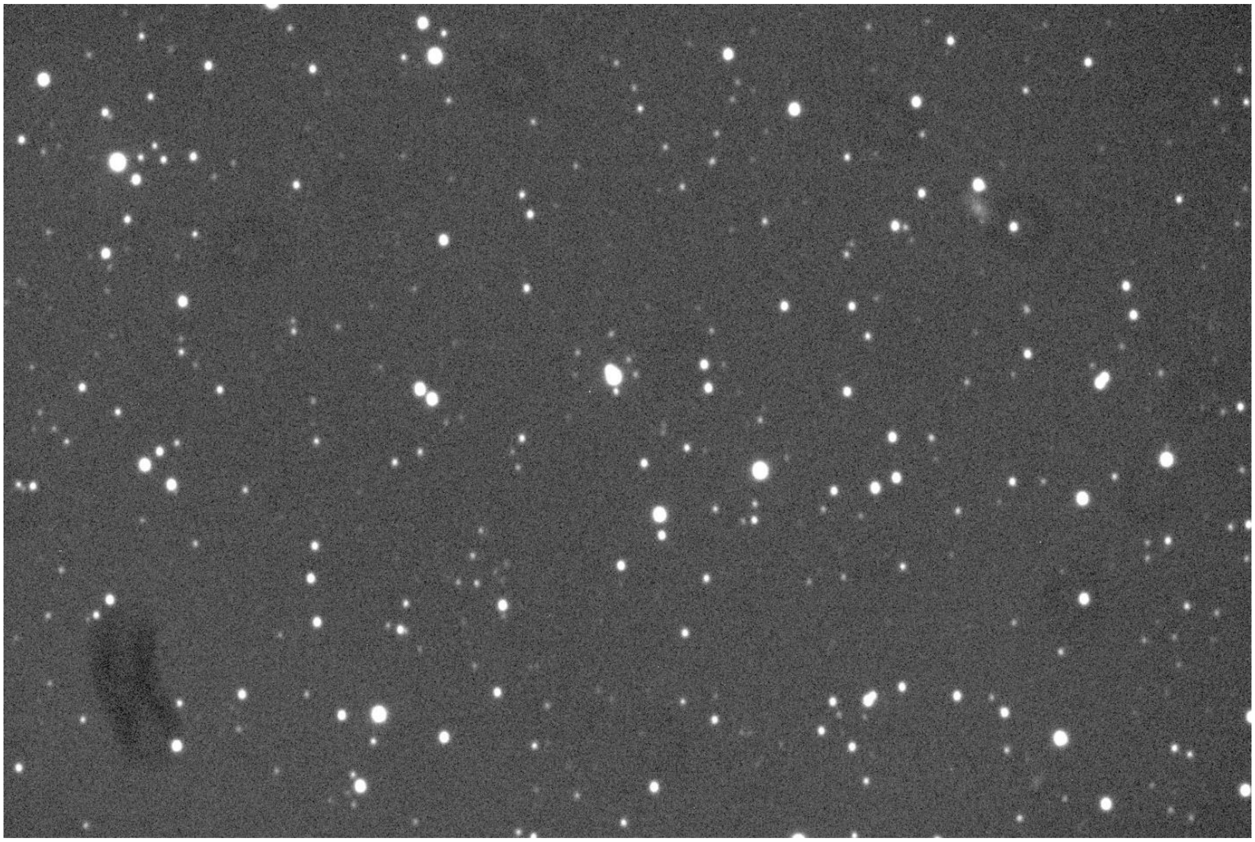
All these resources enable the user to specify the longitude and latitude for an observing site for predictions. ETD provides predictions for any calendar date and will list all transits that can be observed from start to finish at altitudes greater than 20 degrees while the sun is more than 10 degrees below the horizon. TAPIR provides similar predictions by default, but can select for a range of dates, can select according to transit depth, and can specify object names for predictions. TAPIR can also select events according to specific altitudes and hour angles and levels of night time darkness.

At RFO we are currently using ETD and TAPIR to identify exoplanet transits that can be observed using the RC20 telescope.

HATP-20

This is the name of the target that was observed at RFO using the RC20 telescope on the night of April 10, 2024. The observing run began at 10:08pm and continued until 01:11am (on the morning of April 11). The exposure time for the images was 120 seconds. According to the AAVSO, this star has a V magnitude of 11.33 and a spectral type of K3V. The orbital period for its planet is 2.875 days.

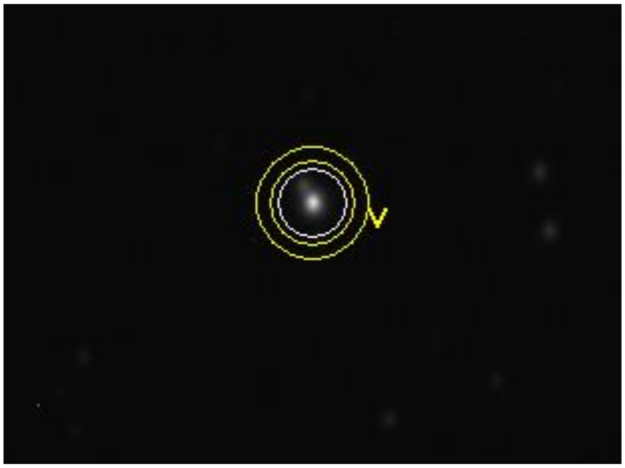
Here is one of the images from this dataset.



Note the image defects resulting from dust on the optical components of the instrumentation. These are the so-called "donuts" visible throughout the image. The smear in the lower left corner was ultimately determined to be a whisker on the camera window. Many of these defects have now been eliminated after an engineering work party at the RC20 on April 16-17.

The target object (HATP20) is the bright object nearest the center of the frame. Note that its image is slightly elongated. It turns out that HATP20 has a prominent companion and is a known double star (WDS J07277+2420A). Astrometric observations indicate this is not a physical double star and is just a chance alignment of two unrelated stars. Brightness measurements for the transit observations used a large enough aperture to safely include both components.

Here are the apertures used for the analysis of this set of observations centered on the target HATP20. Both components are visible.

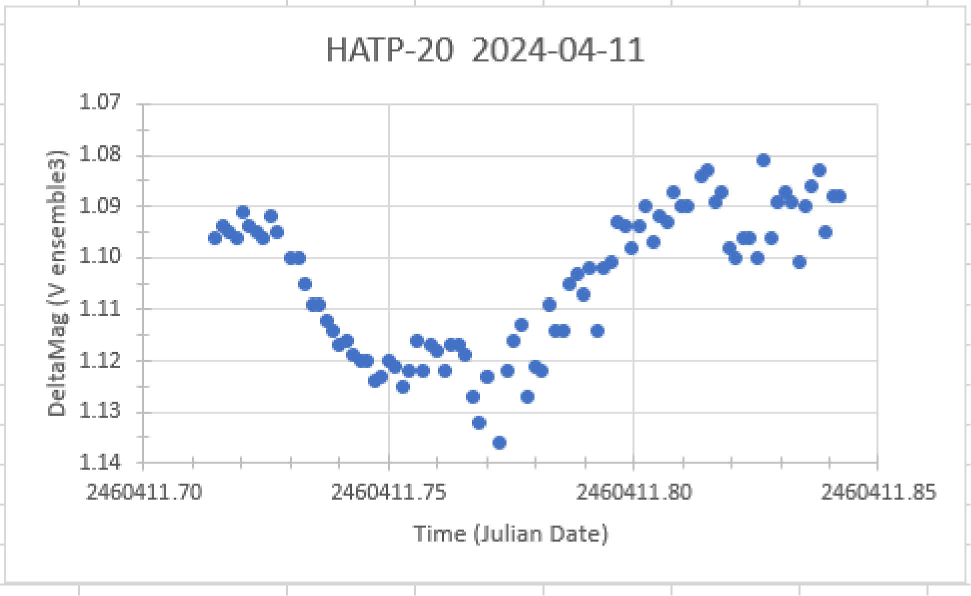


The analysis aperture has a radius of 17 pixels, and the sky annulus ranges from 21 pixels (inner) to 28 pixels (outer). A smaller analysis aperture might have been acceptable, but this larger aperture will always safely include the companion. The separation between the two components is approximately 7 arcseconds. According to the WDS, the brighter component of HATP-20 has a V magnitude of approximately 11.80 while the companion has a magnitude of 13.80. There is a 2 magnitude difference in the brightness of the components. The combination of the magnitude of the two components results in a magnitude of 11.33.

The additional source of brightness due to the companion will diminish any observed brightness variation. The true brightness decline for a transit will be greater than what is observed for observations of the two components.

Here is a preliminary result for the transit curve for the RFO data for April 11.

The RFO transit observations reported here were analyzed using the **Astronomical Image Processor for Windows (AIP4WIN)**. This software for Windows is currently available at no charge from the developer.



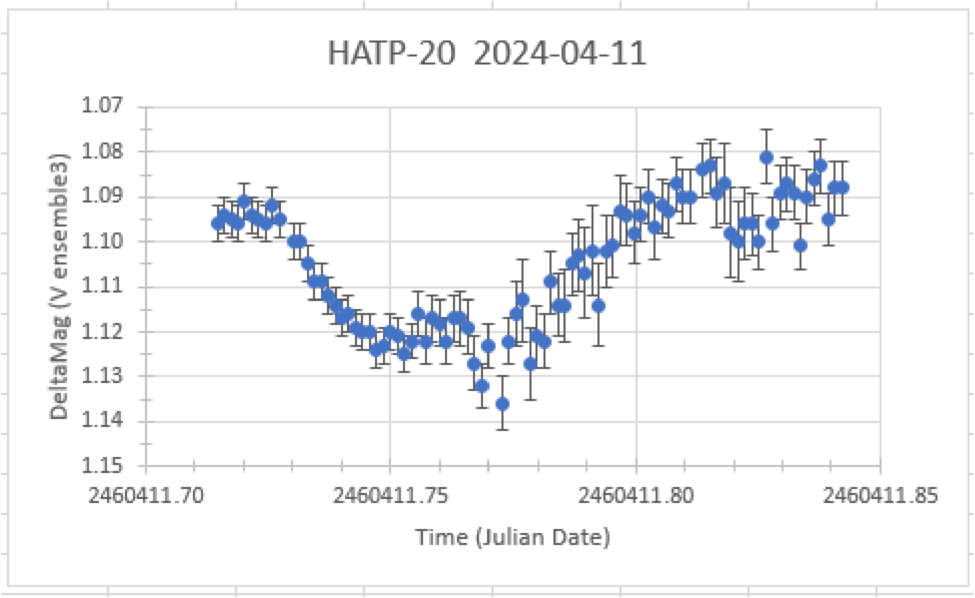
The major tic marks for the time axis (Julian Date) are approximately one hour. The major tic marks for the brightness axis are for 0.01 magnitude. The brightness axis shows DeltaMag (magnitude difference) in V for HATP-20 with respect to the ensemble magnitude for three comparison stars.

Unfortunately, clouds came in during the observing run. Beginning approximately midway through the transit the noise level increases dramatically due to the ongoing passage of high clouds

However, the transit curve clearly indicates a **depth of 0.027 magnitude**. This depth is in agreement with other recorded observations of transits for this object. This depth of the transit is a direct measurement of the relative size of the planet with respect to its star.

The reference brightness for this analysis is the ensemble magnitude for the three selected comparison stars. The ensemble magnitude is approximately 11.928, so the transit curve shows HATP-20 before the start of the transit is approximately 1.095 magnitude fainter than the reference ensemble, or a magnitude of 13.023. These are instrumental magnitudes, which are approximately 1.631 magnitudes fainter than the standard magnitudes. This would indicate a V magnitude for HATP-20 of 11.39, which is consistent with the published magnitude values for HATP-20. Standard magnitudes have not yet been derived for this RFO data.

Statistical errors have been determined by the analysis for each data point so that error bars for the brightness values can be plotted.



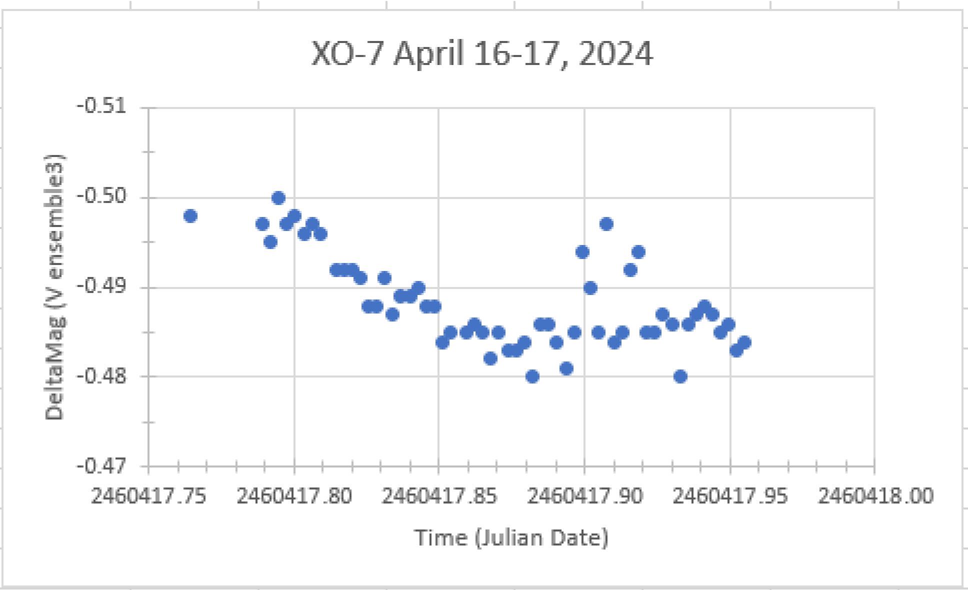
The data clearly shows the increase in the quantified errors after the arrival of the clouds.

The errors prior to the arrival of the clouds are quite good. They are reported as +/- 0.004 magnitude. This is just a few thousandths of a magnitude. We here at RFO are capable of doing milli-mag photometry!

XO-7

A transit was also observed for the object XO-7 on the night of April 16. Observations began at 11:18 pm and continued until 03:53 am on the morning of April 17. The star has a V magnitude of 10.52 and a spectral type of G2. The orbital period of the planet is 2.864 days.

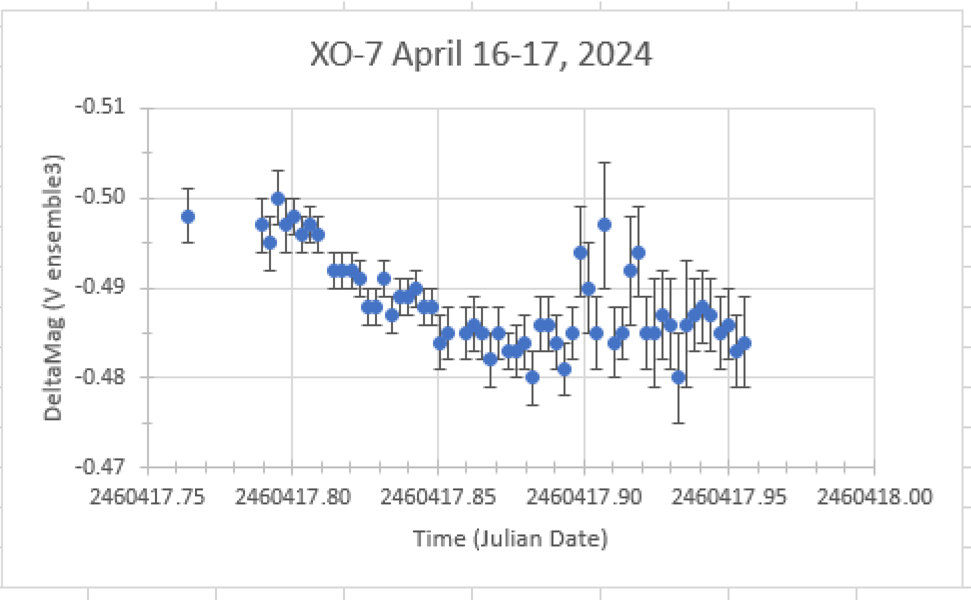
Unfortunately, clouds also came in during the observing run.



The major horizontal tic marks are slightly greater than one hour (1.2 hours, or one hour and 12 minutes). The major vertical tic marks are 0.01 magnitudes. Three comparison stars were used for the reference (ensemble) brightness.

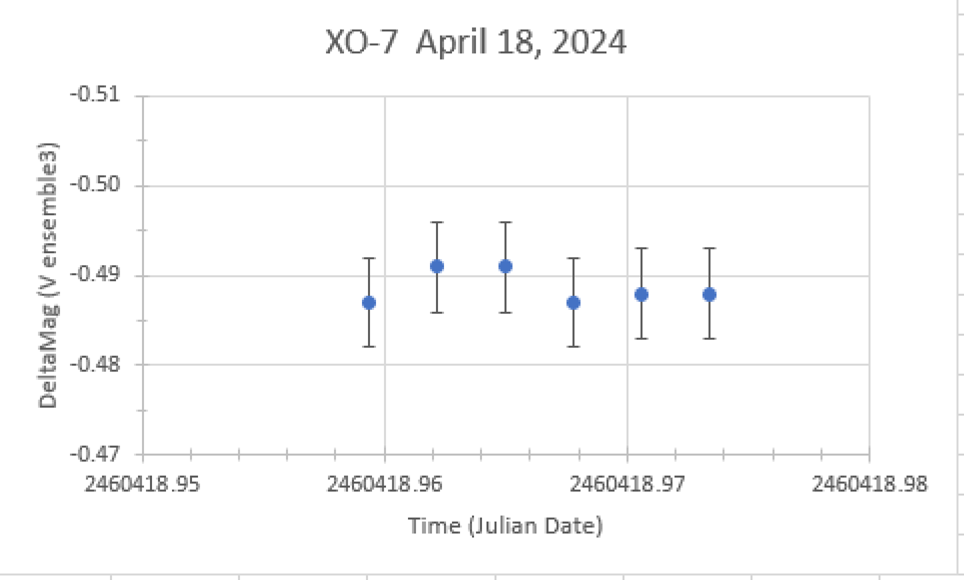
The transit appears to begin at about 24 minutes after midnight (JD2460417.8079). The **transit depth is approximately 0.014 magnitude**. Indications of clouds can be noticed at a time that should have been near the end of the transit. The transit was predicted to have ended by 03:10 am on the morning of April 17 (JD24617.9233). However, the brightness does not return to pre-transit levels. This transit was definitely detected, but an anomaly is present. After the planet left the disk of the star at the end of the transit, the brightness should have returned to pre-transit levels. But the brightness remained at the lower brightness levels encountered during the transit. **What could cause the brightness of the star to remain at lower levels?**

The formal measurement errors for the observations reflect the presence of the clouds, but do not support measurement errors as an explanation for the anomalous end of the transit. The observations indicate that the star has become fainter.



The differential magnitude during the transit is approximately -0.485. The magnitude preceding the start of the transit, which is presumably the normal brightness for the star, is approximately -0.498.

We attempted to check on this anomaly by observing XO-7 on the following evening. Here are these measurements including errors. These results are based on the ensemble using the same three comparison stars for the reference brightness.



The measured brightness (DeltaMag) for XO-7 on April 18 was approximately -0.489 +/-0.002, which is only slightly brighter than the transit level brightness of -0.458 on April 17. The pre-transit brightness is about- 0.498, so the star was fainter by about 0.01 magnitude. Our observations show the star remained fainter after the planet transit on April 17. XO-7 was fainter than its brightness prior to the transit observation on April 17.

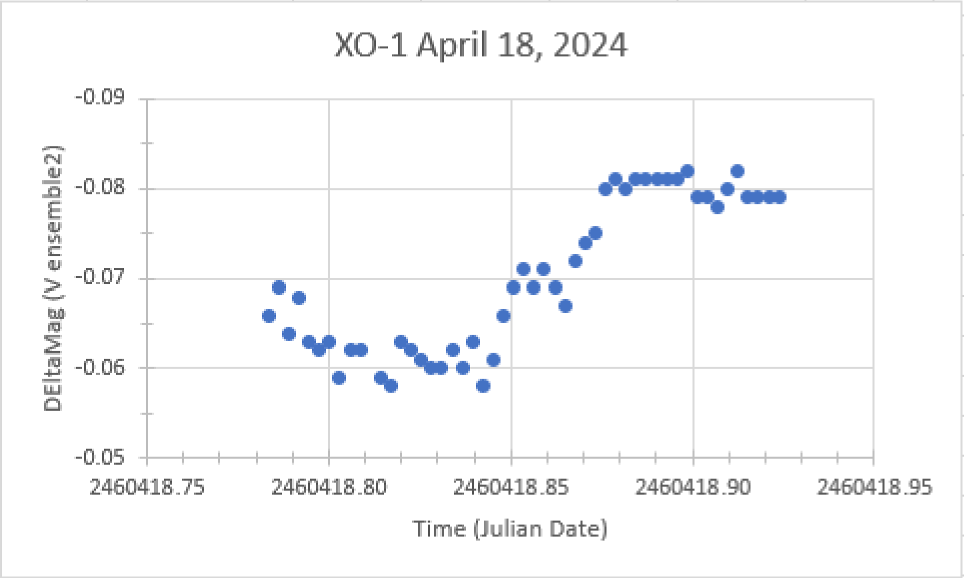
It is our intention to continue to monitor XO-7 to determine whether decreased brightness levels will continue. Furthermore, The planet causing the XO-7 transits has an orbital period of 2.864 days, so transits will occur nearly every 3 days. Not all transits will be observable, but 6 complete observable transits are predicted from April through July 2024. We intend to observe additional transits for XO-7 to monitor its behavior.

XO-1

A transit was also observed for the object XO-1 on the evening of April 17. The V magnitude for this star is 11.30, and its spectral type is G1V. The orbital period for this planet is 3.942 days.

As a result of training and engineering activities on the telescope, observations could not begin until after the transit had begun. Observations began at 11:46pm and continued until 03:08am on the morning of April 18. The camera had not been adequately focused after the engineering activities, but the analysis apertures could be set large enough to produce acceptable photometric measurements.

The analysis described here is based on a reference brightness based on an ensemble consisting of two comparison stars.

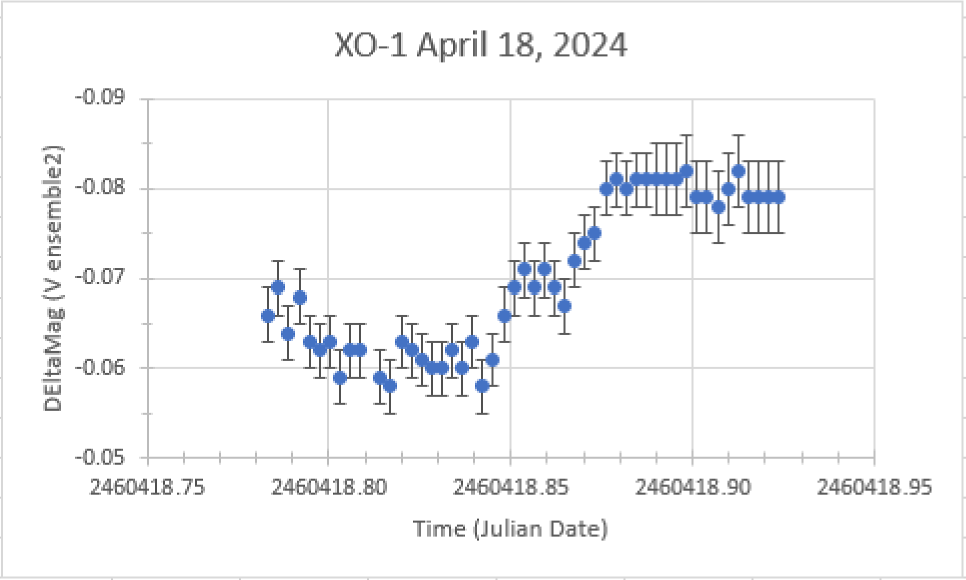


Main tic marks are approximately one hour for time and 0.01 magnitude for brightness.

The object returns to (presumably) pre-transit brightness levels by the end of the transit at 02:06 am on the morning of April 18 (JD2460418.8835). **The approximate transit depth is 0.021 magnitude**.

But an anomalous bump appears during the egress from the transit.

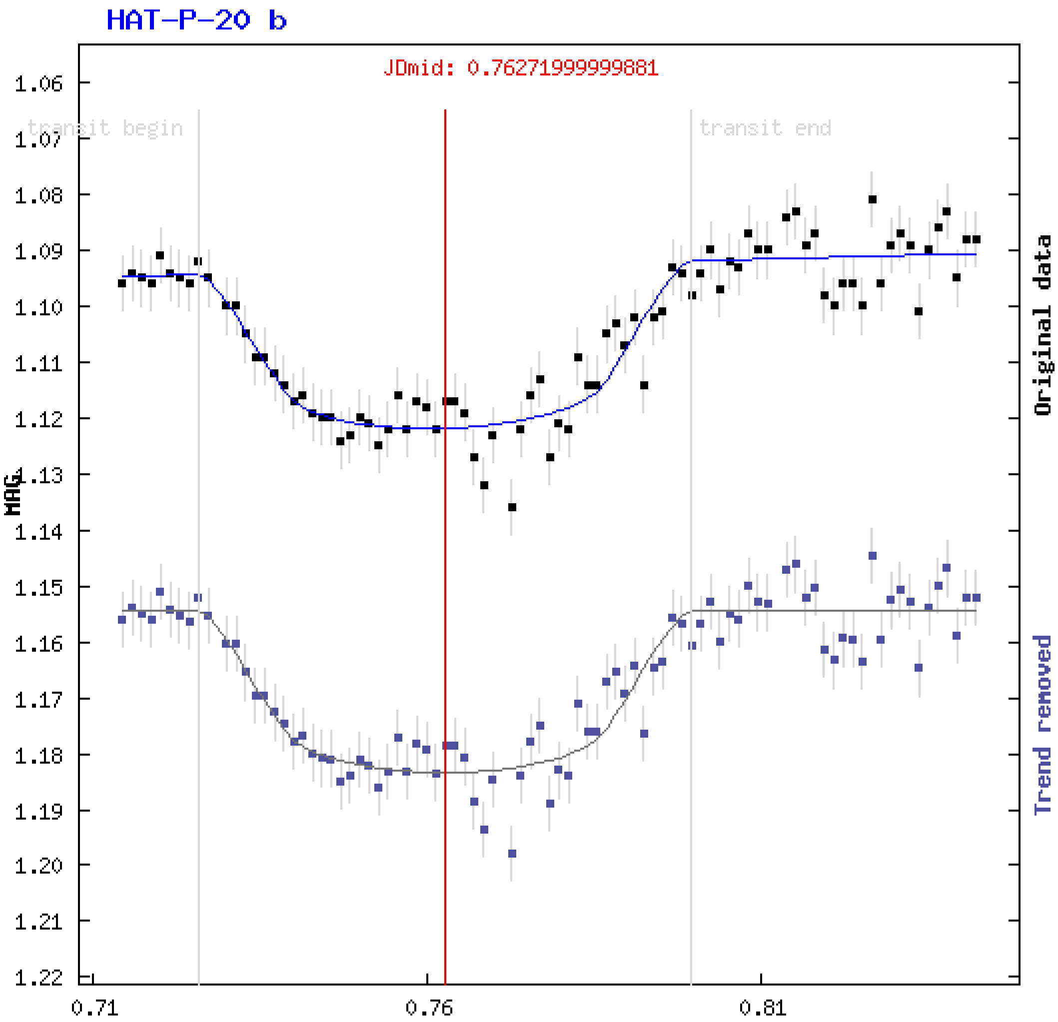
Here is a representation of the error bars based on a formal evaluation of the measurement errors.



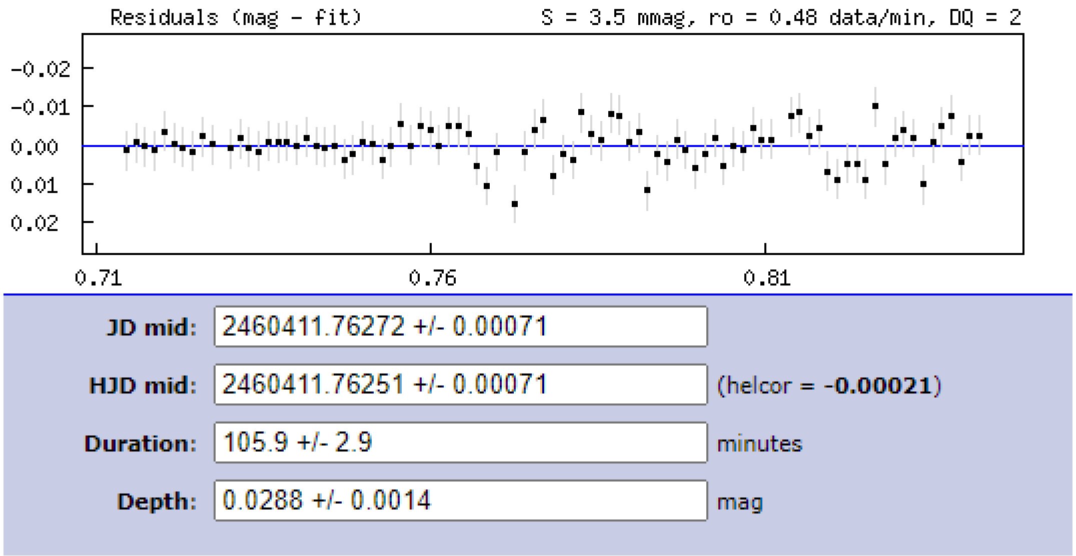
The error bars indicate that the bump on the egress is indeed real, and is not an artifact of measurement errors. **What could cause a bump on a transit curve?**

Simple model fit for our HATP-20 observations

We have been able to fit a simple model to our HATP-20 observations. This model will determine the time of mid-transit, the duration of the transit, and the depth of the transit.



The model produced the following results.



JD mid: 2460411.76272 +/- 0.00071

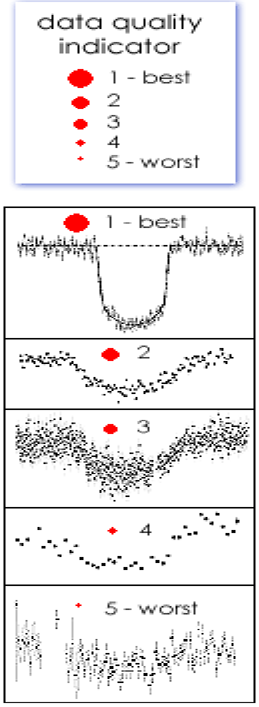
HJD mid: 2460411.76251 +/- 0.00071 (helcor = **-0.00021**)

Duration: 105.9 +/- 2.9 minutes

Depth: 0.0288 +/- 0.0014 mag

The standard error of the fit is 3.5 milli-mag. The parameter DQ, which is indicated along with the residuals, is the evaluated quality of the data and the fit. Our data has been assigned a quality of DQ = 2, which is excellent.

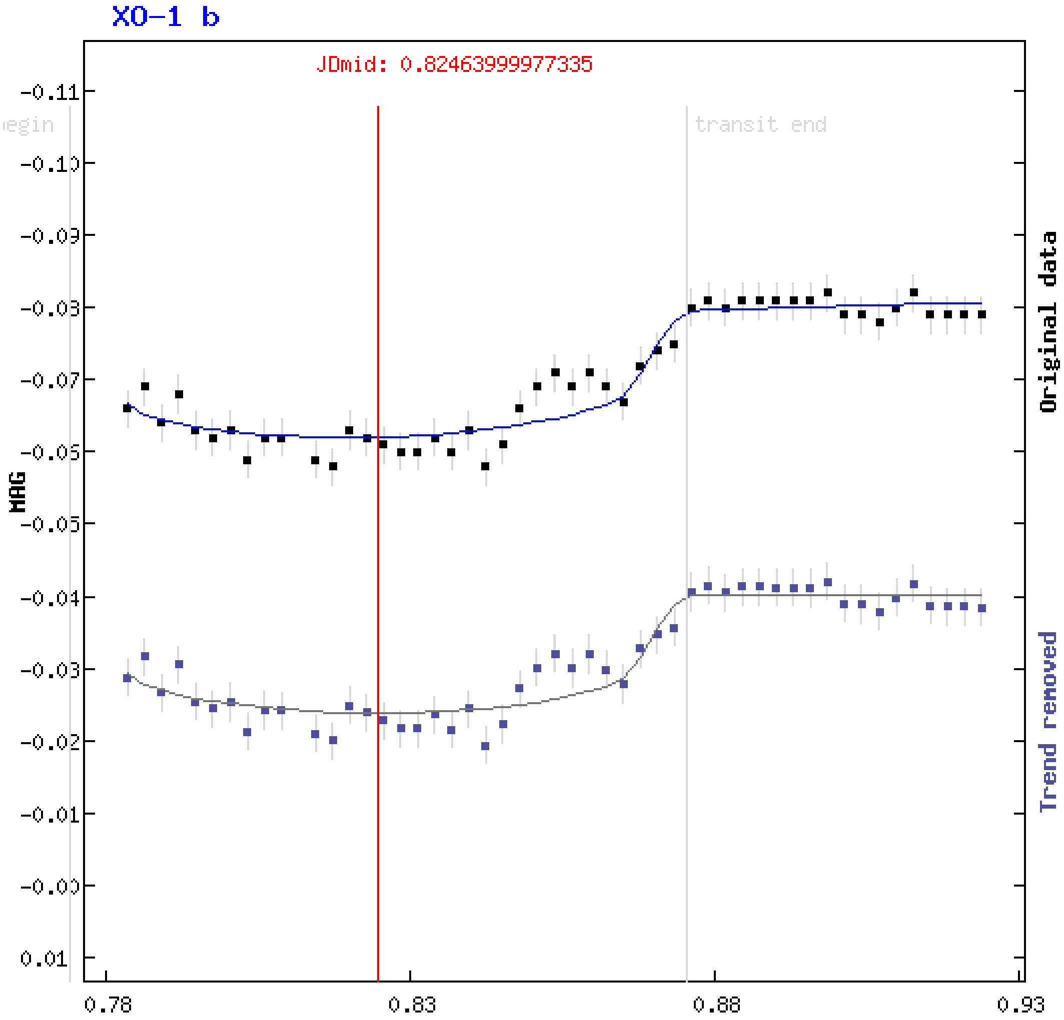
Here is an example of typical transit curve quality assignments.



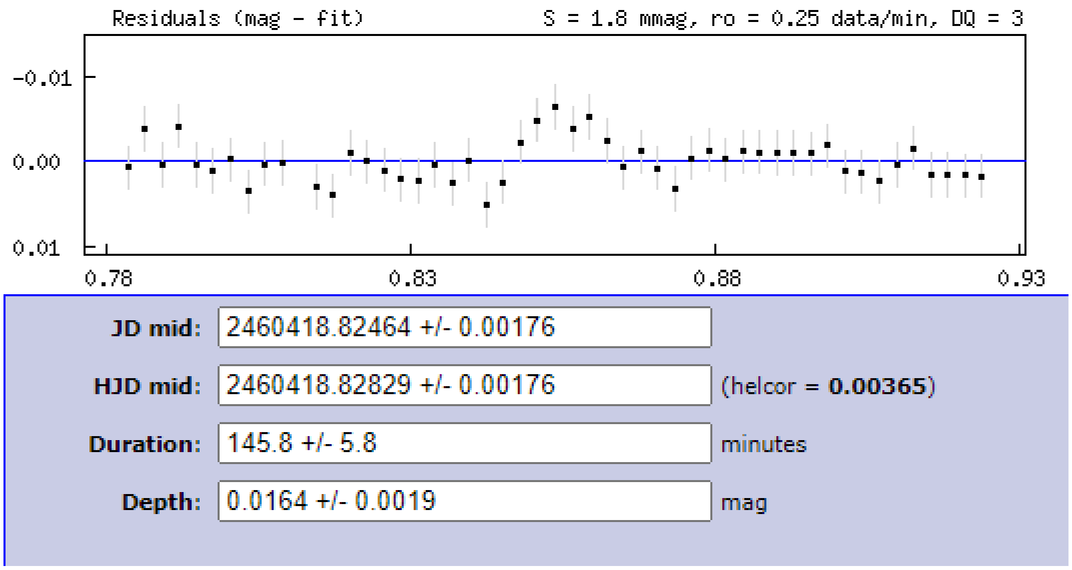
Our results compare extremely favorably with previous transit observations for this object. Even with the presence of clouds, our RFO data was very high quality and produced meaningful results for evaluating the nature of this extrasolar planet.

Simple model fit for our XO-1 observations

Even though our observations did not begin until after the transit had begun, a meaningful model fit to our data was possible.



The standard error of the fit is 1.8 milli-mag. The model parameters resulting from the fit are consistent with previous transit observations for XO-1.



JD mid: 2460418.82464 +/- 0.00176

HJD mid: 2460418.82829 +/- 0.00176 (helcor = **0.00365**)

Duration: 145.8 +/- 5.8 minutes

Depth: 0.0164 +/- 0.0019 mag

There are slight differences from the nominal parameters, but this is likely due our inability to record the start of the transit. Because of the absence of the beginning of the transit this data and fit was assigned a quality factor of 3 (out of 5).

Residuals are greatest in the vicinity of the bump during egress. This supports the suggestion that this bump is a real feature of this transit curve.

No model fit for our XO-7 observations

It was not possible to fit a simple model to our XO-7 observations. The simple reason for this failure is that a transit egress was never observed. The brightness of the star did not return to pre-transit levels by the time the transit was expected to be over. This anomalous behavior warrants continuing evaluation. We intend to attempt to record future transits.

XO-7 was discovered to be orbited by an exoplanet in 2019. The only available transit data since the discovery was recorded 14 October 2023. XO-7b is a Jupiter mass planet with a 2.864 day orbital period. The system also apparently has a second massive planet on a wide orbit.

The next predicted transits observable at RFO will be: Monday May 6, Thursday May 9, Wednesday May29, Tuesday June 18, Monday July 8, and Thursday July 11.

Conclusions

1 – During April 2024 we here at RFO have reliably detected and observed transits for three exoplanets. These exoplanets are all Hot Jupiters, with sizes and masses comparable to the planet Jupiter. These three all have orbital periods of only a few days, and must thus be orbiting extremely close to their star.

2 -- At RFO we can regularly achieve milli-mag photometry on the RC20 telescope. This is achievable for differential photometry using BVRI filters and the new science camera (ZWO ASI2600). Such observations can obtain statistical measurement errors of a few thousandths of a magnitude. Of course, high clouds or other atmospheric phenomena can degrade this capability.

3 -- Transit observations with a V filter can achieve high quality model fits and precision determinations of time of mid-transit, transit durations, and transit depths. Transit depths lead to the determination of relative sizes for the transiting planets, and transit timing and duration can lead to the discovery and monitoring of additional planets present in the planetary system. Irregular features in the transit curves can be used to evaluate non-uniformities on the stellar surface (spots, active regions) and the presence of material in the planetary orbit and in the orbital plane.

4 – Two of the three objects we have observed appear to have anomalous transit curves. XO-1 appears to have a bump in the transit curve which could indicate the presence of features on the surface of the star or material in the orbital plane of the planet. XO-7 did not return to pre-transit brightness levels after what should have been the end of the transit. This could indicate the presence of material in the orbital plane or could be related to the second massive planet in the system on a wide orbit.

5 -- The large number of known systems with transiting planets, and the availability of convenient software, makes it feasible to expect that on any clear night it should be possible to identify a planet which will be experiencing an observable transit. Really! If it is clear, and the RC20 is available, it should be possible to record the transit of an exoplanet.

6 – A large number of Hot Jupiters are present in our Milky Way galaxy. Such star-huggers are not present in our planetary system, and are therefore a newly discovered class of objects. What might we learn by observing this newly discovered class of planets? These objects are easy for us to detect and observe at RFO.