Detection of Transits of Extrasolar Planets

1. Scientific Background

Planets that transit the disks of their host stars offer a unique opportunity to measure extrasolar planetary radii. Together with dynamical mass measurements from the Doppler planet-detection method, one can then measure a planet's density and determine its internal composition. With very sensitive spectroscopic observations, transits also allow astronomers to determine the atmospheric composition of the plant, as the host star's light passes through the atmosphere around the planet's disk.

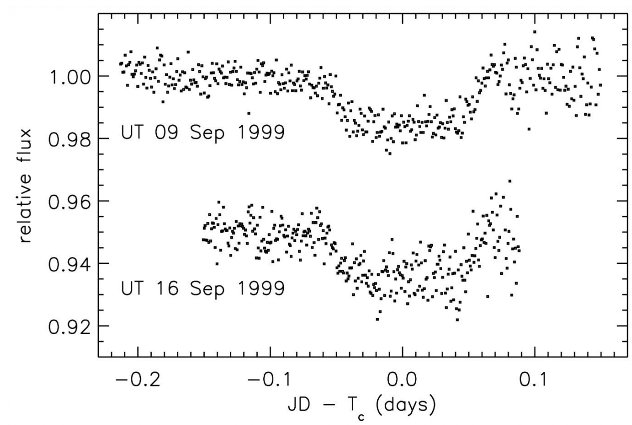

Fig. 1.— Photometric time series for HD 209458 encompassing the transit of its hot Jupiter planet for 1999 September 9 and 16 plotted as a function of time from the mid-transit time T_c. The rms of the time series at the beginning of the night on September 9 is roughly 4 mmag. The increased scatter in the September 16 data relative to the September 9 data is due to the shorter exposure times. The data from September 16 are offset by -0.05 relative to those from September 9. (*Reproduced from Charbonneau et al. (2000).*)

The transit technique is also highly efficient in discovering new planets. While the probability that our line of sight toward any given star falls along the plane of any orbiting planets is very small, that is offset by the sheer number of stars in our Galaxy. And while the first detection of an extrasolar planet transit (Fig. 1; Charbonneau et al. 2000) was of a planet previously discovered through the Doppler method, the transit technique is now very successful in discovering new planets on its own right.

In this experiment you will see how extrasolar planets can be detected and studied with only modest astronomical equipment. A search for new transiting planets is time intensive. However, you can easily confirm the existence of known ones with our Department's 14-inch telescope.

2. Experiment Goals and Plan

This is a precision measurement experiment that exemplifies the power of repeated observations. The design is conceptually and technically simple, yet highlights the need for accurate calibration and control of systematic errors when performing a precision measurement.

2.1. Experiment Goals

- detect the transit of a know hot Jupiter-type planet, checking whether it has the predicted mid-transit time and duration;
- estimate the planet/star radius ratio from the transit depth.

2.2. Experiment Plan

1. Plan on which known transiting planet you will observe. An up-to-date list of known transiting planets is maintained at http://exoplanet.eu/catalog-transit.php. You want to choose one that stays above an elevation of $\approx$40° above the horizon (airmass $\lesssim$1.6) from the Mt. Stony Brook Observatory latitude ($40°56'$) for the entire duration of your observations. You will also want to choose a relatively bright host star ($V \lesssim 12$ mag) with a moderately deep transit signature ($\gtrsim$0.01 mag). You can access relevant data (star's coordinates, V magnitude brightness, planet and stellar radii) by clicking on the "more data" tab in the upper right corner of the table. Download the table, and compute the transit signatures and transit durations. (You can use topcat, excel, python, or a program/language of your choosing for this step.) Which stars are the best candidates for a detection? Predict future transit times for your target stars based on the known planet period and time of first observed transit (best done in a programming language such as python, awk, ...). Use the python script on the class website (rdj2aau.py) to convert the star's R.A., Dec, and the transit dates to Altitude, Azimuth, and UTC times. Select the transits that have good visibility for the entire transit. Plot your star's altitude vs. time using the StarAlt tool (http://catserver.ing.iac.es/staralt/index.php), and mark the transit beginning, mid-point, and end. Triple-check your calculation. You would not want to spend 5 hours in sub-freezing temperatures only to learn later that your calculations for the transit were wrong.

   See also point 9 below: you will need a separate guide star for your observations, within $\approx$0.4° of your science target and brighter than $V \sim 10$ mag.

2. To avoid falling victim to bad weather, select at least three dates on which you can observe the transit within the time limits of you lab. This may well require you choosing more than one potential transit planet target.

3. Print out approximately $60' \times 60'$ finder charts for your targets. Finder charts will facilitate your ability to locate your targets quickly at the telescope. Visual (V) band finder charts can be downloaded from the Simbad astronomical database by following the "basic data" link off the webpage for each planet on the http://exoplanet.eu site.

   Alternatively, having a running copy of the Stellarium software centered on the target star will also help. **A finding chart is essential** because the telescope pointing can be off by a degree or more if it has not been properly aligned in the recent past.

4. Acquaint yourself with how to operate the Mt. Stony Brook 14-inch telescope, the SBIG STL-1001E CCD camera, and the CCDSoft program on the telescope laptop. Instructions are linked off the course website.

5. Make sure to come to the telescope at least 2 hours before your planned observations. Start up the telescope. Mount the CCD and change the telescope focus as necessary. (Read the step-by-step telescope operations linked off the course webpage.)

6. Verify that the computer's clock is synchronized with the official atomic clock time (http://www.time.gov/).

7. Take the necessary CCD calibration images: "flats" and "darks" (see §3). The latter may best be taken at the end of the night when you know what exposure times you have used for your science images. For your flats (but not your science images), you may wish to use "auto-darks".

8. Find your star. Depending on your experience with the telescope and the CCD, this may take from one to many tens of minutes. Plan accordingly! Take a test image to determine how long you can expose without saturating. Aim to stay **below 50%** of saturation to avoid saturating the CCD (and hence losing flux information) if a significant improvement in atmospheric transparency occurs. If the star is very bright, you may (slightly!) defocus the telescope in order to maximize the signal while avoiding the non-linear part of the response curve. If conditions change significantly during the night, you may wish to adjust your exposure time / focus. Note that you have to take darks for each exposure time that you used for your science images.

9. Establish guiding (or tracking) on a nearby star in the autoguiding CCD. Make sure to read the quick-start guide to using CCDSoft linked off the course website.

   Finding a suitably bright star can be very tricky! The autoguiding CCD has a factor of $\approx$5 smaller field of view than the imaging CCD. It functions as a fully independent CCD, with its own exposure time setting. The position of the autoguiding CCD is beyond the top edge (positive y values) of the science CCD. You may need to rotate the orientation of the CCD camera on the telescope to find a guide star. The existence of a suitable ($V \lesssim$11 mag) guide star within $\approx$0.2° of your science target may in fact be an important limitation in your choice of science target!

10. Take a long sequence of unsaturated exposures of your science target, ideally staring 0.5–1 hour before the beginning of the expected transit, and finishing another 0.5–1 hour after.

11. Take flats, if you didn't in the beginning of the night, and if necessary, darks for the exposure durations that you used (see §3).

12. **Park the telescope**, Remove the CCD camera from the telescope, and bring all instruments back to the storage room.

13. Transfer your saved .FIT files to a memory stick for further processing.

3. Data Acquisition

The data are acquired over the course of approximately one half night with the 14-inch telescope housed in the dome on the rooftop of the Earth & Space Sciences Building. The observational approach is trivial: acquire the target star near the center of the CCD field of view, and take repeated unsaturated exposures of the field for the entire duration of the transit, plus 0.5–1 hours before and after. To maintain the same set of reference stars in the field of view, you will need to guide the telescope on your science target star or a neighboring bright star for the entire duration of the experiment. This can be done with the tracking CCD of the SBIG camera and the CCDSoft program that is installed on the telescope laptop.

To calibrate the varying response to light of the CCD pixels, you will need to take "flat field" exposures at the beginning of the night. You can either take these directly on our light-polluted night skies or on the illuminated dome interior. In either case, take a series of at least 10 long exposures followed by an equal number of short exposures. The long exposures should have pixel counts of $\sim$30% of the saturation threshold, while the short ones should be at around 10% of saturation.

Make sure that you also have a set of "dark" frames with the corresponding exposure durations for your calibration and science images. Darks can be obtained automatically by the CCD after each exposure, with the saved image file being the difference between the "light" and the dark exposure, or can be obtained separately at the end of your observations. Taking darks immediately after each exposure effectively doubles the time to get any single exposure, but may be convenient for short observations. For long ($\gtrsim$30 sec) exposures you may find it more practical to take a single set of darks at the end of the night.

Make sure to keep a good observing log in your lab book. In particular, proper records of exposure sequence starts and durations with one-minute precision is crucial. Do not rely on the computer to keep record of time through the information saved in the headers of your image files, as the computer may not be synchronized with local time.

For specific instructions on the use of the equipment, see the telescope and CCD manuals linked off the course website: http://www.astro.sunysb.edu/anja/PHY517_AST443/.

4. Data Reduction

The data reduction steps include:

1. generation of a master flat field and a bad pixel mask from the calibration flat-field exposures;
2. applying the master flat and the bad pixel mask to all of the science data;
3. finding all point sources (stars) in each individual science exposure and determining their centers;
4. determining the optimum aperture size for measuring fluxes;
5. measuring the flux of each point source using aperture photometry and proper subtraction of the sky background;
6. obtaining the light curve of your science target (the planet host) relative to the flux measurements of the rest of the point sources (calibration stars).

The data reduction can be done in python or in IDL. Talk to the instructor if you would like to use something else. Starter code is distributed in python; you will have to edit this code in order to complete the data reduction. For instructions in IDL, see http://www.astro.sunysb.edu/metchev/PHY517_AST443/transit_planet_lab.pdf.

4.1. Image processing

Generating a Master Dark You should have obtained a series of "dark" exposures with the same exposure time as your science images. You need to median-combine these into a Master Dark (*why is a median better than a mean for these images?*). Locate the corresponding function in the python starter code, complete the missing line(s), and use it on your images. If your science images have different exposure times, generate one MasterDark for each distinct exposure time.

Generating a Master Flat and a Bad Pixel Mask You should have obtained two series of flat field calibration exposures before your observations (§3): one with a high mean flux level per pixel, and one with a low flux level. Both of these sets should have been taken so that dark exposures should already have been subtracted from them.

Generating a Master Flat Field. Median-combine your high-count rate flat fields. That is, for each pixel in an image, take the median number of counts in the same pixel across all high-count flat field images. Median-combination gives you a high-fidelity estimate of the ∼average count rate and the median is less sensitive to outliers (e.g., due to cosmic ray hits) than the mean. If your flat field images have varying levels (e.g. because they are twilight flats), you need to rescale them first to a common level, such as by normalizing each image by its median.
Normalize the median-combined flat by the mode (or median, or mean) of the number of counts. This is your Master Flat.

Processing the Science images Apply the Master Dark and Master Flat to the Science images.

Generating a Bad Pixel Mask. On an ideal CCD detector the counts in each pixel between the two sets of flat fields should scale as the mean (or median) of the counts in all pixels. Actual CCD detectors have bad pixels, which are areas of the detector in which the linear response is compromised.

To find the bad pixels, divide the median-combined high-count flat field image (i.e., before normalization) by the median-combined low-caount flat field image. The value of each pixel would ideally equal the ratio of exposure times. (The exposure time is listed in the FITS header for each file, keyword EXPTIME.) Examine the histogram of the pixel values in the ratio image; the outliers (e.g., >5–10σ from the mode) are bad pixels. Outliers can also be identified as "hot" pixels in the MasterDark frames, and "dead" pixels in the MasterFlat.

Create a bad pixel mask by generating an array equal to the dimensions of the individual images, and setting good pixels to '1' and bad pixels to '0'.

4.2. Aligning the Images

If the auto-guider did not work perfectly during your observations, the position of the star on the CCD will vary from exposure to exposure. To avoid having to manually find the star on each image, you can solve for the WCS (World Coordinate System) of your image. The easiest way to do so is to submit your images to http://nova.astrometry.net/. This service will determine the position of your images on the sky, and return an image with the correct WCS header keyword. You will then be able to identify your star based on its (R.A., Dec) coordinates in each image.

Note that you can also download the astrometry.net software. A local copy is installed on the *uhura* machine at the Astro Computing Center (see the class webpage for instructions on how to use it).

4.3. Photometry

Use Source Extractor (http://www.astromatic.net/software/sextractor) to identify and measure the properties of objects in your images. Source Extractor (SExtractor) returns a catalog of objects in an image, along with measurements of their position, magnitudes, fluxes, sizes, etc.

4.4. Aperture Photometry on Your Target and Calibration Stars

To set the extraction aperture, load up one of your exposures in ds9. Locate your star, and draw a 'circle' region file around it. Adjust the radius of the circle so that it encompasses most of the star's light as evident on the `zscale` setting. Make sure that no other object is located within (or too close to) the circle (you may have to try different scale parameter settings in ds9 to visualize the dynamic range of the image). Read off the radius of your circle - this will be the aperture for your flux measurements.
Note that this procedure gives a larger aperture than the one that optimizes the statistical signal-to-noise in this particular image; however, a larger aperture is more robust against seeing variations. Verify on a few images taken throughout the night that your aperture is a good match.

Adjust your Sextractor configuration file to measure flux within your chosen perture (note that SExtractor specifies the aperture's diameter, not radius). Run SExtractor on all images. Concatenate the output files to create a table of time, flux, and flux error for your planet-host star. If your images have been WCS-corrected, use the (R.A., Dec) coordinates to match up objects in this step.

Also pick ~ 10 reference stars of similar brightness. Make sure all reference stars are visible in all images. Generate lightcurve tables also for your reference stars.

4.5. Calibration of the Science Target Photometry; Light Curve

For each reference star j, rescale both the flux and error on the flux by the star's average flux over the length of the observations, $\langle f_j \rangle$:

$$f_j(t) \to \frac{f_j(t)}{\langle f_j \rangle} \qquad ; \qquad \sigma_{f_j(t)} \to \frac{\sigma_{f_j(t)}}{\langle f_j \rangle}$$

This step helps to visualize the relative variations due to changes in airmass, the atmosphere, as well as any intrinsic variations of stellar brightnesses. Inspect the light curves of all calibration stars, and remove any reference stars that display more than random variability over the observing period. Also identify individual exposures that are significantly different from others (e.g. the flux in all stars is zero) and remove them from the analysis. To visualize more than one star on the same plot, you can offset the lightcurves of a given star by adding or subtracting a constant value (see Fig. 1 as an example).

From these plots, you can see that changes in atmospheric conditions cause flux changes that are as large or larger than the signal you are trying to detect. By calculating the flux of the target stars *relative* to the reference stars, you can account for these atmospheric changes. By averaging over several reference stars, you reduce the statistical noise as well as systematic uncertainty from undetected variability in the reference stars. When computing the average flux of several stars, you want to take into account the statistical weight of each, i.e. you want to compute the weighted mean

$$\mu_i^{\rm ref} = \frac{\Sigma_j f_j^{\rm ref}/(\sigma_j^{\rm ref})^2}{\Sigma_j 1/(\sigma_j^{\rm ref})^2} \tag{1}$$

and the corresponding error on the weighted mean,

$$\sigma_i^{\rm ref} = \sqrt{\frac{1}{\Sigma_j 1/(\sigma_j^{\rm ref})^2}} \quad . \tag{2}$$

In a separate text file record: (1) the time of observation for each image i (header keyword DATE-OBS), (2) the flux $f_i^{\rm sci}$ and error of the science target, (3) the weighted mean of the (rescaled) fluxes of the calibration stars for image i, and (4) the ratio $r_i = f_i^{\rm sci}/\mu_i^{\rm ref}$ and its error.

Identify the images taken before and after the expected transit times. These images are used to calculate the baseline flux of your target star (similar to the flux normalization that was done for each reference star). Calculate the baseline flux, and normalize r_i (and its error) by it. Now, the ratio r_i represents the fraction of light from your science target that is not obscured by the transiting planet. That is, r_i should scatter around 1.0 out of eclipse, and around $1.0 - \epsilon$ during eclipse. The value of ϵ gives the planet/star geometric size ratio and is the quantity sought in this experiment.

Use the above data to plot the raw light curve of your science target. Try binning your data into 2-min, 5-min etc. intervals to bring out the transit. In this case, use the actual data to estimate the error on the mean by calculating the unweighted average, and the unweighted error on the mean.

5. Analysis and Discussion

5.1. Transit Detection

Depending on the quality of the obtained data, the transit may be readily evident in your light curve as a $\approx$1% dip below the out-of-transit stellar flux as in Figure 1, or may appear indistinguishable.

If the transit is evident, then check the transit times against the predictions. Variations (of order seconds) in the times of ingress and and egress could be linked to the gravitational influence of other, yet undiscovered planets in the system, and would be very interesting!

If the transit dip is not immediately evident, try to detect it by using the known mid-transit time and transit duration. For the purpose, compare the mean of all of your in-transit measurements to the mean out-of-transit brightness of the star. In comparing the means and their standard errors you seek to establish whether the in-transit flux is significantly smaller than the out-of-transit flux. Make sure to use the appropriate statistical test when comparing two means and their standard deviations.

If the transit is still not detectable, place an upper limit on the transit depth using the expected transit mid-point and duration.

In order to be able to make a statistically robust conclusion here, you need to correctly propagate measurement errors throughout your data reduction and analysis.

5.2. Planet Radius

Using your determination of the transit depth, estimate the planet-to-star radius ratio, or an upper limit to it if the transit was not detected. Compare your estimate to the known value for the transiting planet from the astronomical literature. You may find the NASA Astrophysics Data Service literature search tool useful (http://adsabs.harvard.edu/abstract_service.html), and in particular the "object name" search feature.

5.3. Discussion

Discuss whether your detection or limit is consistent with the literature value. If not, discuss possible sources of systematic error that may affect the measurements. If the transit was readily evident, discuss whether you detect any transit time variations, their magnitude, and significance.

REFERENCES

Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. 2000, ApJ, 529, L45
