

# Lab #4: Detecting a transiting exoplanet using CCD Images

10/15/2012

Your report is due on November 06, 2012 at 5:59 PM PDT.

## 1 Overview

One of the most exciting new topics in the field of astronomy is extrasolar planets (“exoplanets”). One of the ways we can detect and gain information about exoplanets is by observing planets that *transit*, or pass in front of their stars from our point of view. During the transit, the light we receive from the star is dimmed by up to 1-2%, providing critical insight on the properties of the planet.

In this lab we will use CCD images from the 1m Leuschner Observatory telescope to try and detect the transit of an extrasolar planet and determine the planetary radius. In practice, we will use a “differential aperture photometry” technique to produce a *light curve* (a plot of stellar flux as a function of time) depicting the dip induced by the planetary transit (see Figure 1). This document presents step-by-step instructions to prepare, conduct, and analyze astronomical observations with a CCD camera.

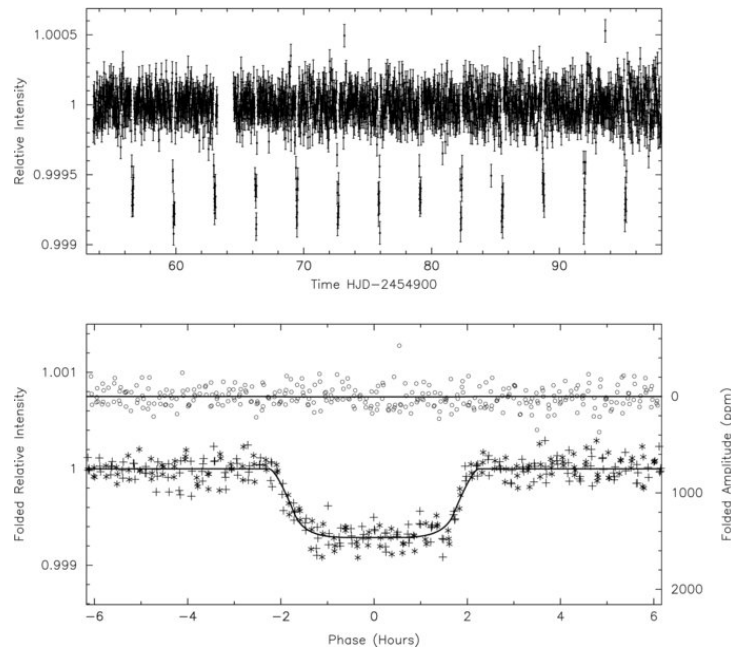


Figure 1: (*Top*) Light curve for KOI 4 obtained by the space-based Kepler mission. Notice how the star dims by less than 0.1% (!) every  $\sim 3$  days. (*Bottom*) A “phase-folded” light curve, in which all eclipses have been shifted so as to be perfectly superimposed onto one another (crosses and star symbols). The transit for this system lasts about 4 hours. The open symbols represent the lightcurve of the system in opposition of phase from the transit (i.e., when the planet disappears behind the star). From Borucki et al. (2010).

### 1.1 Key steps

The key steps are:

- 1) Get familiar with the Leuschner Observatory telescope and CCD camera (§2);
- 2) Select appropriate transiting exoplanet targets for the Leuschner 1m observations (§3);

- 3) Gather Leuschner 1m observations of the transiting exoplanet systems (Oct 17-22, weather permitting);
- 4) Read FITS files from the telescope and display the data using IDL (§4.1);
- 5) Apply systematic corrections including dark current and flat field corrections (§4.2);
- 6) Re-align all images so that each star lies at the same pixel location in all images (§5);
- 7) Use an automated routine to measure the flux of the target and reference stars in all images and generate the lightcurve of the target star (§6);
- 8) Determine whether the transit is detected, estimate its depth and, consequently, the radius and average density of the exoplanet, placing constraints on its nature (§7).

## 1.2 Schedule

This is a three-week lab. Steps 1 and 2 above are to be done today, in preparation for step 3 later this week (see class schedule). The remainder of the activities will start next Tuesday, with a show-and-tell presenting the result of the eclipsing binary measurements. You should aim at having completed (at least) step 6 above before the last week of the lab.

## 1.3 Recommended reading

Howell, *Handbook of CCD Astronomy*, chapter 4 & 5, especially §§5.1, 5.2 and 5.4

# 2 Getting familiar with the Leuschner Observatory

We will be using the 1m telescope at Leuschner Observatory<sup>2</sup>. The telescope is equipped with a 4008 × 2672 pixel CCD. The resultant field of view is approximately 20 × 13.4 arc minutes. Under typical observing conditions, we can use binning by a factor of 2 to reduce the readout overheads. Details of the facility are listed in Table 1.

**Table 1: Nominal observatory and instrument properties. A x2 binning factor is generally used.**

Site	Russell Reservation, CA
Geographic location	37:55.1 (N) -122:09.4 (E)
Primary mirror	1 m (diameter)
Detector	SBIG STL-11000M-C1 CCD
CCD format	4008 × 2672, 9 μm pixels
Pixel scale	0.3 arc seconds/pixel
Binning factors	1.5 e <sup>-</sup> /pix/s at T=0° C
Field-of-view	20 × 13.4 arc minutes
Readout time	30s (x1 binning) 5s (x2 binning)

## 3 Target selection

Before we observe the transiting exoplanet systems, we have to decide which target we will point the telescope at. In this lab, our goal is to obtain a lightcurve for a known exoplanet, as opposed to searching for a new transiting exoplanet. This would require us to monitor many thousands of stars in order to detect just one transiting system! For such endeavors, dedicated telescopes (and space missions such as the Kepler mission<sup>3</sup>) are built and used exclusively for this purpose.

<sup>2</sup> See <http://ugastro.berkeley.edu/leuschner/index.html> for more details about the Observatory

<sup>3</sup> <http://kepler.nasa.gov/>

To decide which target we will look at, we will use the Exoplanet Transit Database<sup>4</sup> (ETD), which contains a large amount of information on already known transiting exoplanets. We will provide you with a listing of all known transiting planets observable this week (Oct 17-22), from which we will pick the most promising systems. Pay attention to the fact that this website, as many professional astronomy catalogs and databases, uses Universal Time (UT) to avoid confusion with the local time that varies from one observatory to the next. While we are in Pacific Daylight Time, UT is 7h ahead of us. So sunset, which is around 6:30pm this week, occurs at 1:30am UT, with the date a day ahead (i.e., it is already Oct 17 in UT time!).

To identify which transiting exoplanet(s) can be observed on each night this week, browse the list of predicted transit from the ETD database. You should pick the best candidate for each night based on the following criteria:

- The depth of the transit must be as large as possible to improve our chances of detecting it. Ideally, the selected targets will have depths of 0.01 mag (~1%) or larger.
- The target must remain high in the sky throughout the transit. Observing a star very low on the horizon introduces larger fluctuations in sky transparency and poorer image quality, which in turn introduces larger uncertainties in the measured fluxes. A common criterion in astronomy is to observe objects when they are above an elevation of 30°.
- We must be able to observe the star at the very least 30min before and after the transit (transit times on the ETD are only good to within 5-10 minutes, typically).
- The transit duration should be as short as possible to avoid changing weather conditions.

We will have a lab-wide discussion on the best candidates for each night and each group will sign up to observe one object between now and next week's lab. Since each transit lasts for 2 to 4h, we can only observe one (or two) transits per night, so it's important to choose wisely the best candidates! After your group has selected its science target, make sure to create a "finding chart" that shows the star and its neighboring field so you can confirm that you have acquired the right object. Aladin<sup>5</sup> is good tool to create finding charts (create one that has about twice the field-of-view of the Leuschner camera to ensure that slightly inaccurate pointing does not throw you away).

For the observations, follow the procedures demonstrated during class. Refer to the telescope and software manuals for any problem you might encounter or for more details on the variety of options available to you. It is always a very good idea to read these manuals prior to observing, to have things fresh in your mind.

## 4 First look at the data and calibration images

### *Summary of Section 4 Instructions:*

- Read in all files and transform using `b scale` and `b zero` or `/f scale`
- Compute the bias and dark current rate for the Leuschner CCD
- Generate master dark current images
- Create a master flat-field

### 4.1 FITS headers

CCD images are saved on disc in a standard astronomical format, known as FITS (Flexible Image Transport System) files. FITS files contain the image data, stored in binary format, together with some information that records the circumstances under which the data were obtained. Although the image data in FITS files are in binary format, each file also has an ASCII preamble that can be conveniently inspected at the Unix command line by typing, for example:

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<sup>4</sup> <http://var2.astro.cz/ETD/>

<sup>5</sup> <http://aladin.u-strasbg.fr/aladin.gml>

```

ugastro% fold image101.fits | more
SIMPLE = T / NORMAL FITS IMAGE
BITPIX = 16 / DATA PRECISION
NAXIS = 2 / NUMBER OF IMAGE DIMENSIONS
NAXIS1 = 1056 / NUMBER OF COLUMNS
NAXIS2 = 1024 / NUMBER OF ROWS
[...]
END

```

The header includes useful information about the size of the image (NAXIS1 & NAXIS2), the date (DATE-OBS), the exposure time (EXPTIME), where the telescope was pointing (RA & DEC), the optical filter in the light path (FILTER) and the binning factors used along the rows and columns directions (XFACTOR and YFACTOR, respectively). The header contains “keywords,” e.g., FILTER, that have values on the right hand side of the equals sign.

Scrolling through the ASCII FITS header in a terminal is fine for browsing, but if you want to use information in the FITS header in your IDL program, you will need to read the keywords. This is accomplished with the IDL function `SXPARR`, e.g., to find the object name

```

IDL> x = readfits('image101.fits', hdr)
or
IDL> x = mrdfits('image101.fits', 0, hdr)
% READFITS: Now reading 1056 by 1024 array

```

Two very important keywords in the header of our image are `BSCALE` and `BZERO`. Each image you read using the `MRDFITS/READFITS` function should immediately be transformed using the following equation:  $x_{\text{real}} = x * BSCALE + BZERO$ . **NB:** this transformation is done automatically if you use the `/fscale` option of the `mrdfits` function instead.

## 4.2 Bias, darks, & flats

During the night we acquired various calibration frames, including bias, darks, and flats.

**Bias Frames:** A bias frame is a zero second exposure (or as short as the camera allows), which measures the number of counts the detector reads with no signal. These frames can be used to determine which parts of the detector are affected by significant electronic. Compute the median and pixel distribution of bias values.

**Dark Exposures:** A dark exposure is an image of non-zero exposure time where the shutter does not open, and is a measure of the dark current in the system. The dark signal (which contains the bias level as well) needs to be subtracted off all data images. Because the amount of dark current signal is proportional to time, the dark exposures need to be of the same exposure time as your data images, or else must be constructed by adding a bias and an appropriately scaled “dark-bias” image.

The Leuschner CCD camera is cooled by a thermoelectric cooler to a temperature of typically  $-17^{\circ}$  to reduce the electronic dark current. Use the bias and dark images to estimate the actual level of dark current per pixel and per second. For the integration time used during the observations, generate a “master” dark image that will be subtracted off every image obtained during the night.

**Flat Frames:** Flat frames are images taken with the telescope pointing at a blank wall or at a region of the sky without any stars, often the horizon during twilight. The flat frames are a measure of the pixel-to-pixel response of the camera. You may see stars in your sky flat frames. Computing the median of all flat-field images will remove any star and produce a “master” flat-

field that you can divide all your data images by to correct for the variation in pixel response across the CCD. Make sure the master flat-field is normalized, i.e., that its median value is unity.

## 5 Selecting reference stars and aligning all images

### *Summary of Section 5 Instructions:*

- Subtract the master dark from all images and apply flat-field correction
- Correct images so that the average background count is zero, if necessary
- Find the locations of the science target and 5-10 reference stars to within  $\sim 1$  pixel
- Align all images so that all stars remain at a fixed location (to within  $\sim 1$  pixel)

NB: these operations apply to images of both the “test” eclipsing binary and the “science” transiting exoplanet system.

### **5.1 First look at the data and selection of “reference” stars**

Inspection of a data image reveals a few to a few dozen stars (depending on the location of the target in the sky). After subtraction of the master dark and division by the master flat-field, are the background counts exactly zero? Is that what you expected? If it is not null, the background must be brought down to zero. How do you perform this? Once this is done, what is the noise per pixel in the background? The resulting images are “clean”, i.e., they have corrected for all known electronic “features” of the CCD camera. What is the apparent FWHM of stars in our images (this is what astronomers call the “seeing”)? Note that this quantity should be expressed in arcsecond, not in pixels (only the former is independent of the instrument used).

To construct the lightcurve of our targets, we will compare its flux to that of other stars (“reference stars”) in the image in order to correct for variations induced by other factors than the transiting exoplanet. For instance, thin clouds may come in and out of the direction toward the target. Also, as we follow the star over the course of its diurnal motion, our line of sight crosses a varying amount of atmosphere. Since the transmission of the atmosphere in the visible range is not a perfect 100%, this implies that our observations will suffer from a time-dependent transmission. By picking reference stars in the same field-of-view as our target, we can monitor *in real time* and calibrate out these variations. This method is called “differential photometry”, since the fluxes we will measure are not calibrated on an absolute scale.

To select reference stars, you should pick the brightest (unsaturated) stars in the image. The more reference stars, the better, but only to the extent that their flux can be measured with good precision (i.e., avoid faint or saturated stars!). Selecting 3-5 reference stars is a good number, although the exact number depends on the field that was observed and your own preferences. For the eclipsing binary system, using a single reference star is sufficient. Record the position in the image of the science target and of the reference stars to a precision of  $\sim 1$  pixel or better. Which method did you use to determine the location of the stars?

### **5.2 Aligning all images**

While we were obtaining our observations, the tracking system of the telescope compensated for the Earth’s rotation and the guiding system applied finer corrections to maintain the stars in a constant location on the detector. Nonetheless, these corrections were not perfect and the location of any given star varies throughout our observations. Select a few images and check how large this effect is in your data.

In order to use a fully automated photometry routine, we must correct for this continuous “jitter” (if it is larger than half the seeing halo or so), since otherwise using an aperture at a fixed location will not provide reliable measurements. Which method can you think of to estimate the displacement of any individual image compared to a “reference” image (the one you have

worked with so far, for instance)? Keep in mind that, given the large number of images we have to deal with, it is important that this process be as automated as possible. Once you have determined the necessary displacement, use the command `SHIFT()` to apply it.

Once you have selected (and tested) an alignment method, process all images through this alignment correction. We now have a collection of images that are corrected for all electronic effects and in which the stars are all in a constant location on the detector.

## 6 Generating the light curve

### *Summary of Section 6 Instructions:*

- Determine the optimal aperture radius using a bright, isolated star
- Compute the flux of the science star and each of the reference stars for every image
- Compute a weighted average of the flux of the reference stars for each image
- Compute and plot the flux of the science star relative to the weighted average of the reference stars as a function of time

Again, this section applies to both the eclipsing binary and transiting exoplanet system. Work with the eclipsing binary first, since you only have a couple of images and the difference in flux should be much larger than that of the transiting exoplanet.

### 6.1 Aperture photometry

We must now measure the flux of the science target and of the reference stars. As you can see from your images, the light from each star doesn't fall on one pixel but rather is spread over many. In order to get the total light from each star, we need to integrate the signal from all these pixels. After we define the location of the star, we will simply add up the signal from all the pixels within a certain radius of this peak. However, defining the radius of each star on your image can be tricky; too small a radius means that we are leaving out some of the starlight, while too large a radius implies increasing the amount of noise by adding pixels that contain little stellar flux. The analysis of starlight by adding up the flux within a certain radius on an image is known as *aperture photometry*. One way (but not the only one) to compute the flux in a given aperture consist in defining a "mask" images (whose value is 1 inside of the aperture and zero outside) which can be used as follows:

```
IDL> Flux_star = total(img * mask)
```

To select the aperture radius, try using many different radii and determine which is best, as follows: Select a well-isolated and relatively bright star in the image (this can be the science target or one of the reference stars) and write a program that 1) computes the total flux in a circular aperture for a range of increasing radii, 2) estimates the total noise (this includes the background noise for each pixel in the aperture and the Poisson noise on the total number of *electrons* – not *DNs*, remember to use the detector's gain!) and 3) plots the resulting signal-to-noise ratio (i.e. [integrated flux]/[total noise]) as a function of aperture radius. Which aperture radius do you plan on using and why?

### 6.2 Generating the light curve

We are now ready to measure the flux of the test and science targets and their respective reference stars in each cleaned image. Write a program that computes these fluxes for each image, as well the associated uncertainties (again, combining background and Poisson noises). In addition, to take advantage of the fact that we selected several reference stars, we must compute some form of weighted average of their fluxes to improve the precision of our results. One

method consists in using  $1/\sigma(F_i)^2$  as a weight<sup>6</sup> to the individual flux measurements  $F_i$ . However, this is appropriate for our purposes only if the various reference stars have the same brightness. Otherwise, the selected weighting scheme will put more weight on the fainter stars (which has the smallest absolute flux uncertainty). To circumvent this problem, first normalize the light curve (and associated uncertainties) of each reference star to its median flux across your observations. Now the fainter star will have the less weight since its uncertainty will be larger.

Store the results (fluxes and uncertainties for each star, plus the weighted average of the reference stars) in a file, along with the time at which each image was taken (using the information located in the header). The function `PRINTF()` and `READF()` can be useful at this point.

Since we assume that the reference stars are intrinsically not variable (generate plots for each reference stars to test whether this assumption is correct), any variation in the ratio between these two fluxes is intrinsic to the science target. Compute and plot the ratio of these two fluxes as a function of time, along with its uncertainty. This is the lightcurve we have been trying to construct all along!

## 7 Analysis

Do you see any variation of the flux of the exoplanet host over time? Can you *quantitatively* demonstrate that we have detected the transit of the exoplanet in front of its parent star? How (hint: consider separately the “in transit” and “out of transit” data)? Is this consistent with the expected depth of the transit from the ETD database? Note that, to improve statistics, you may rebin the data (grouping the data in small packets of  $N$  individual images, averaging the fluxes and propagating uncertainties accordingly). If the transit is not detected, place an upper limit on the depth of the transit, i.e., determine the deepest transit that your data would not have been good enough to detect.

If you have detected the transit of the exoplanet, you can now use the light curve to derive some physical information about the planet. At first order, the decrease in flux during transit is a simple geometric effect whereby a small body (radius  $R_p$ ) masks out a fraction of a larger, light-emitting body (radius  $R_\star$ ). What is the relation between  $R_p$ ,  $R_\star$  and the depth of the transit? The best estimate of the stellar radius for your science target can be retrieved from the Exoplanet Encyclopedia<sup>7</sup>. If the radius of the science star has not yet been estimated, assume a radius of 1  $R_\odot$ . What radius, or upper limit, do you infer for the exoplanet (in units of  $R_{Jupiter}$ )? How does it compare with that listed in the Exoplanet Encyclopedia? Given the mass of the planet (also available in the Encyclopedia in most cases), what is the average density of the planet (in  $g/cm^3$ )? Is this planet more like a gaseous giant (like Jupiter) or a rocky planet (like Earth)?

Finally, reflect on how the experiment could be improved to enable a better characterization of the extrasolar planet.

## 8 References

Borucki et al., 2010, The Astrophysical Journal Letters, 713, L126

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<sup>6</sup> To learn more about this choice of weight, read James Graham’s handout on “the Method of Maximum Likelihood” available in the class website.

<sup>7</sup> <http://exoplanet.eu/>