Lab #5 - Detecting Exoplanet Transits

Your report is due Wednesday, March 13, 2019 at 11:59 PM.

1 Overview

In this lab, we will make use of data taken from the William Herschel Telescope (WHT) to observe the transit of a known exoplanet around its host star and measure its transit properties. Our goal is to obtain a light curve for a known exoplanet, as opposed to discover a new transiting exoplanet system. It is not practical to search for new systems, as this would require us to monitor many thousands of stars to guarantee detecting just one transiting one. For such endeavors, dedicated telescopes (and space missions such as Kepler[1]) are built and used exclusively for this purpose.

We will measure the ensuing partial eclipse from the exoplanet by monitoring the brightness of the star as a function of time. We will measure the time when transit occurs and the depth of the eclipse to establish properties of the planet. The purpose of this activity is to learn more about reducing and analyzing astronomical observations and the skills needed to measure very precisely the brightness of an astronomical object on a CCD and (importantly) quantify the precision of the measurement.

1.1 Key steps

The key steps are:

1) Familiarize yourself with the William Herschel Telescope and ACAM data (§2, 3);
2) Apply systematic corrections including bias and flat field to all individual frames (§4);
3) Select reference stars and measure the pixel position of the target star in each image (§5);
4) Write an automated aperture photometry routine to measure the flux of the target and reference stars in all images and generate the light curve of the target star (§6);
5) Estimate the transits depth and, consequently, the radius and average density of the exoplanet, placing constraints on its nature (§7.1);
6) Use advanced modeling code that includes limb darkening to determine planetary properties (§7.2);
7) Interpret and compare your results with these differing methods

1.2 Recommended reading

Howell, *Handbook of CCD Astronomy* (second ed.), chapters 4 & 5, especially §5.1, 5.4, and 5.5
See references in §8.

1.3 Schedule

This is a four-week lab starting on Feb 4, 2019. After reading week, by class Feb 25th, each group should have finished reducing their data sets (steps 1 and 2) and you should aim to have made progress with steps 3–5. By the last week of the lab you should be running the simulation code for comparison and interpreting your final results (steps 6–7).

1.4 Exoplanet transits

One of the most exciting current topics in astronomy is the discovery and characterization of exoplanets. One of the principal methods to detect and characterize exoplanets is by monitoring

[1] http://kepler.nasa.gov/

the brightness of a system where the planet transits, or appears to pass in front of the star. During the transit, the light we receive from the star is dimmed by a factor (δ) of approximately

$$\delta = (\Delta F/F) = (R_p / R_\star)^2$$

where $R_\star$ is the radius of the star, R_p is the planet radius, and ΔF is the change of total flux F. Thus for 0.1 $R_\odot$ planet (e.g, Jupiter), 1% dimming might be typical, and transits provide a way to measure the size of the planet relative to its host star. This estimate is only an approximate value as the brightness of the stellar disk is not uniform and limb darkening must be taken into account for a more accurate value. The impact parameter (b) for a transiting exoplanet is defined as,

$$b = a \cos i,$$

which is a function of the inclination of the orbit (i) and semi-major axis (a), see Figure 1.

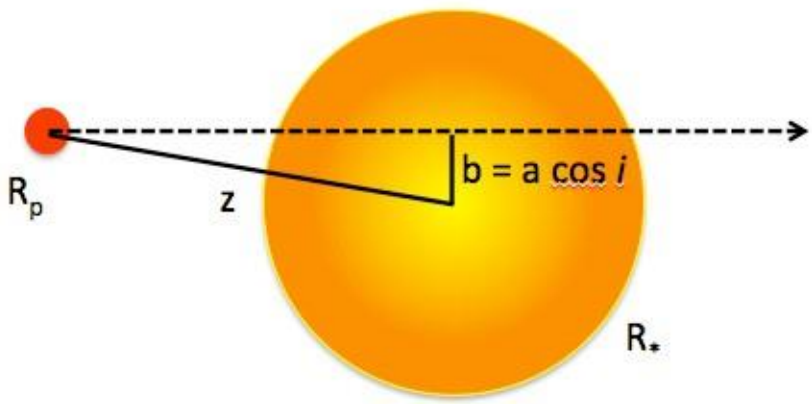

Figure 1: **Illustration of the impact parameter b, where b = a cos *i*, and where z = d/R. The distance between the center of star to the center of the planet (d) and the radius of the star ($R_\star$) The radius of the transiting exoplanet is R_p and radius of the host star is $R_\star$.**

In this lab we will use CCD images from the ACAM instrument on the William Herschel Telescope to detect the transit of an extrasolar planet and determine the planetary radius. In practice, we will use differential aperture photometry to produce a light curve, which is a plot of stellar flux as a function of time that reveals the dimming of starlight induced by the planetary transit (see Figure 2).

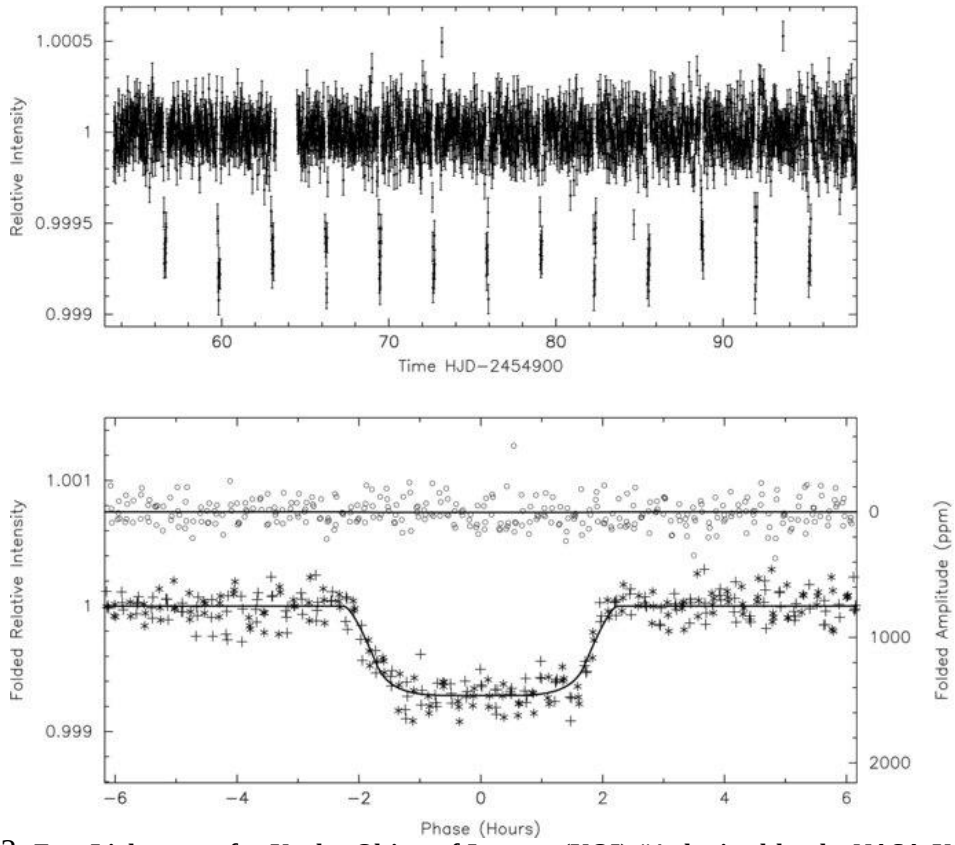

Figure 2: ***Top:*** **Light curve for Kepler Object of Interest (KOI) #4 obtained by the NASA Kepler satellite (Borucki et al. (2010)). Note that the star dims by about 0.09% every 3.2 days.** ***Bottom:*** **A "folded" light curve, where subsequent eclipses have been shifted in time so that they are superimposed. The transit for this system lasts about 4 hours. The open symbols show the light curve when the planet is behind the star.**

2 Imaging Camera on William Herschel Telescope

We will be making use of data from the Auxillary-port CAMera (ACAM) on William Herschel Telescope (WHT), operated by the Isaac Newton Group of Telescope. The WHT was ranked as one of the most productive telescopes in the world from 1990–2001, with the most number of *Nature* journal papers. It is named after Frederick William Herschel (1738–1822) who was a famous astronomer that discovered Uranus, binary stars, and was the first to prove that Newton's laws of gravity were universal.

There are several instruments that can operate behind the WHT telescope, but we will be making use of the optical camera ACAM, which has a field of view ~8 arcminutes in diameter. Your group should make sure they read through the pertinent information about both the WHT and ACAM from the following webpages.

3 GJ 1214 b

We have selected a data set for GJ 1214, a star with a known transiting exoplanet, that was observed on May 23, 2011 (UTC) in the Sloan Gunn *g* filter[2]. The "GJ" stands for the Gliese catalog of nearby stars within ~25 parsec from our Sun. The date of these observations was purposely timed to coincide with a known transit time. Your team will need to make use of the fits header information for this lab (e.g, the time each frame is taken (UTOBS), as well as the

[2]Data courtesy of PI: Prof. de Mooij

exposure time (EXPTIME), and other details to the observations). In the data directory you will find bias frames, flat field frames, and images of the field that contain the target star GJ 1214 with other reference stars. There is a text file in this directory that summarizes each of these fits files. Please review the webpages for both ACAM and WHT.

ACAM: http://www.ing.iac.es/astronomy/instruments/acam/imaging.html

WHT: http://www.ing.iac.es/Astronomy/telescopes/wht/

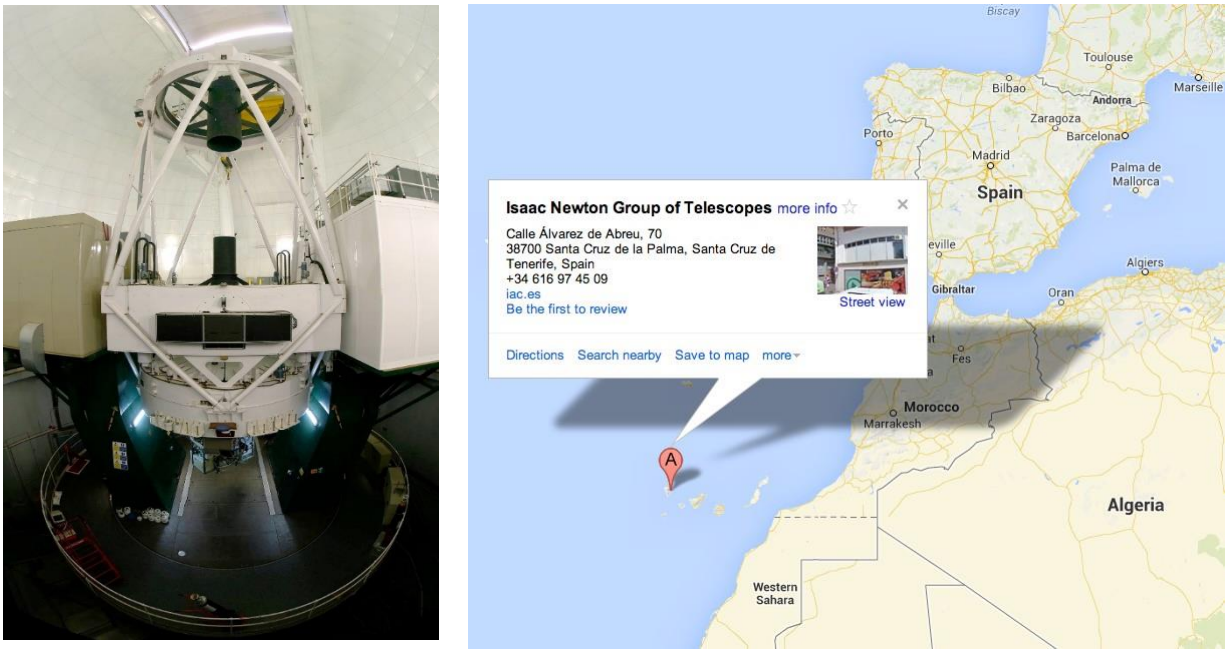

Figure 3*: **Left:*** **Photograph of the William Herschel Telescope (4.2 m). Right: Google map location of La Palma, Spain, where Isaac Newton Group of Telescopes operates WHT.**

Your team can make use of the Exoplanet Transit Database[3] (ETD) to determine the predicated transit times and depth for this star on the observational date. The ETD website shows the list of known transiting exoplanets observable from a specific longitude and latitude. For each entry, it gives the central and final time of the transit (indicated in UT), the duration (D in minutes), the brightness of the star (V mag.), as well as the maximum depth of the transit (0.01 mag corresponds to 1% dimming).

To identify the star GJ 1214 you will need to use existing catalogs to determine the on-sky orientation and stellar field. You can use the RA and DEC in the header information and the Aladin Sky Atlas[4] to perform initial field orientations and stellar identifications.

4 Systematic Corrections: Bias & Flat Field

As we have done in previous labs, we will need to account for systematic sources of error in the image. However, the accuracy we require makes it important to understand the differing contributions of noise from reading from the detector, from the generation of electrons independent of photons hitting the detector, and the differences in how individual pixels react to

[3]Exoplanet Transit Database: http://var2.astro.cz/ETD/
[4]Aladin Sky Atlas: http://aladin.u-strasbg.fr

uniform illumination across the detector. To account for these effects, during the night we will acquired various calibration frames, including bias and flats.

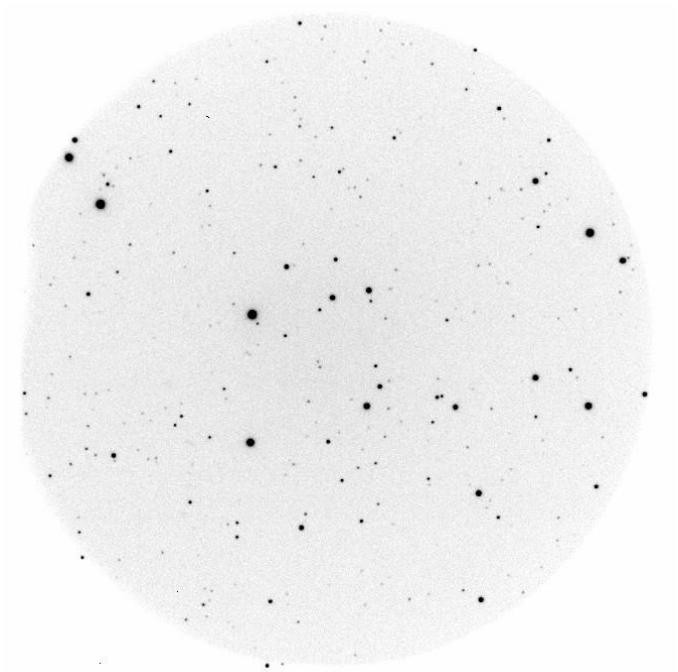

Figure 4*: **WHT ACAM image with a circular field of ~8 arcminutes for GJ 1214 star and field of stars.***

Bias: A bias frame is a zero second exposure, which measures the number of counts the detector reads with no signal. These frames can be used to determine which part of the detector is affected by significant electronic defects. For the detector, compute the median and pixel distribution of bias values.

Flat: Flat frames are images taken with the telescope pointing at a blank wall or at a region of the sky without any stars, often during twilight. The flat frames provide a measure of the relative pixel-to-pixel response of the detector. Because astronomical detectors are very sensitive, you may see occasional stars in twilight flat frames. Computing the median of all flat-field images (make sure to normalize the individual twilight flat frames to be at the same flux) will remove any stars and produce a "master" flat field that you can divide all your data images by and correct for the variation in pixel response across the CCD. By convention, the master flat field is normalized so that its median value is unity.

For ACAM, the field of view is circular since optics vignette the detector (see Figure 4). This means that you should only use pixels in the region that were exposed to the sky. You will have to generate a mask for the field of view on sky and normalize with respect to that region of the detector.

5 Selecting reference stars and correcting for image motion

Now that we have understood some of the sources of noise that may affect our measurement of brightness and obtained the appropriate calibration frames to account for them, we can begin applying these corrections to your science images. During this stage of the lab, monitor the images that are produced in the intermediate steps to ensure that your calibration process is doing

what you expect. The easiest way of doing this is to have your Python scripts save intermediate FITS files and examine them in DS9.

5.1 First look at the data and systematic calibration

Inspection of a data should reveal a few to a few dozen stars. After subtraction of the master bias and division by the master flat field, are the background counts exactly zero? Is that what you expected? If it is not close to zero, the background must be reduced. How can you achieve this? Once this is done, what is the noise per pixel in star free regions? What is the apparent size (in pixels) of stars in our images? Can you use moments, e.g., $<x>$ and $<x^2>$ to make this measurement?

5.2 Selection of "reference" stars

To construct the light curve of our target, we will compare its flux to that of other stars ("reference stars") in the image. This comparison allows us to correct for variations induced by other factors than the transiting exoplanet. For instance, thin clouds drift by obscure the target field. Also, as we follow the star as it rises and sets, our line of sight crosses a varying amount of atmosphere. Since the transmission of the atmosphere in the visible range is not 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 regions of the CCD with hot pixels or other cosmetic defects). Several dozen stars are probably bright enough. You also want to avoid known variable stars. Record the position in the image of the science target and of the reference stars to a precision of 1 pixel or better. Which method did you use to determine the location of the stars?

5.3 Aligning all apertures/Correcting for image motion

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 an automated photometry routine, we must keep track of this drift, since using an aperture at a fixed location in pixel coordinates will not provide reliable measurements.

6 Generating the light curve

Now that we have calibrated the images and determined the stars to use for reference, we are ready to measure the brightness (or flux) of the planetary host in each of the images throughout the night. Since we are looking for very high sensitivity, *how* we go about measuring the flux of the star affects the precision of the measurement. For this lab, it will be sufficient to use a method called "aperture photometry," which is conceptually among the easiest (but by no means the only) ways of determining the flux, but has a number of important parameters to play around with that will affect your final error. Once we have measured the flux of the planetary host in each of the images, we will be able to create a "light curve" or a plot of the star's brightness as a function of time.

6.1 Aperture photometry

We must measure the flux of the science target and of the reference stars. As you can see from your images, the light from each star does not 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:

```
>>> Flux_star = numpy.sum(img * mask)
```

To select the aperture radius, try using a range of 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 (this is called a "growth curve");
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? This should be outlined in your laboratory report. (Note that you may use different aperture sizes for the range of reference stars).

6.2 Generating the light curve

We are now ready to measure the flux of the science target and the 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, compute the weighted average of their fluxes. Store the results (fluxes and uncertainties for <u>each</u> 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).

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 light curve we have been trying to construct all along!

7 Analysis: Determining exoplanet properties

The light curve of a transiting exoplanet can yield important properties and constraints on the planetary system. The following are the primary properties that transit light curves can reveal about the properties of the transiting exoplanet.

- Transit depth yields the radius of the planet, R_p (§7.1)
- Duration of transit yields the inclination (i) and with monitoring the period of orbit (p)

- Estimate the mass of the planet (M_p) since the inclination (i) is constrained, but with better confirmations from radial velocity measurements
- Estimate the density of the planet ρ_p
- The contribution of limb darkening can be estimated by the shape of the bottom of the light curve

7.1 Estimating exoplanet properties with a simple model

Now that we see variation of the planetary host over the course of the observations, we can begin characterizing the planet that is orbiting said star. Do take a moment to contemplate on how this manner of detecting planets was first successfully executed in 1999 for HD 209458 b!

Do you see any variation of the flux of the science target 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 average the data by grouping the data in small sets of *N* individual images, averaging the fluxes and propagating uncertainties accordingly (see Figure 5).

If you detected the transit of the exoplanet, you can use the light curve to derive some physical information about the planet. To 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 $R_\star$). From a simple "top hat" model of dimmed flux during a transit times, measure the following things:

1. What is the relation between R_p and $R_\star$ (eq. 1) and the depth of the transit (i.e., in % of relative flux and magnitudes)?
2. The best estimate of the stellar radius for your science target can be retrieved from the Exoplanet Encyclopedia[5]. What radius, or upper limit, do you then infer for the exoplanet (in units of $R_{Jupiter}$)? What is the uncertainty to your measured exoplanet radius? How does it compare with that listed in the Exoplanet Encyclopedia?
3. Given the mass of the planet and your measured radius, what is the average density of the planet (in g/cm^3)? What does this imply about the composition of the planet?
4. Using the ingress and egress times of the transit what is your measured inclination (i) and period (p) of the exoplanet's orbit?

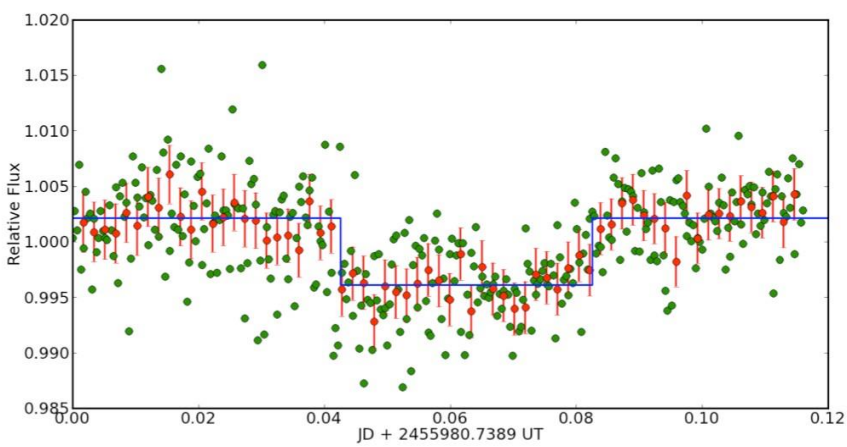

Figure 5: ***Light curve for a transiting exoplanet. You can use a simple "top hat" model to estimate the radius of the planet.***

[5]Exoplanet Encyclopedia: http://exoplanet.eu/

7.2 Light curve modeling that includes limb darkening

During the exoplanet transit the planet occults different portions of the stellar disk, as illustrated in Figure 1. Limb darkening from the host star and the impact parameter (b) from the eclipse will also affect the shape of the light curve. The optical depth (τ) for any given viewing angle across a stellar disk probes a different depth into the star's atmosphere. This effectively means that at each location across the stellar disk the observer is looking at a different effective temperature and density of the star, which means that the flux per wavelength is a function of line-of-sight position along the stellar disk. Limb darkening refers to the decrease of flux as you observe from the center of the stellar disk to the edge or "limb" of the stellar disk. During a transit of the exoplanet this means that the amount of flux dimmed at time (t) is a function of what part of the stellar disk the planet is eclipsing.

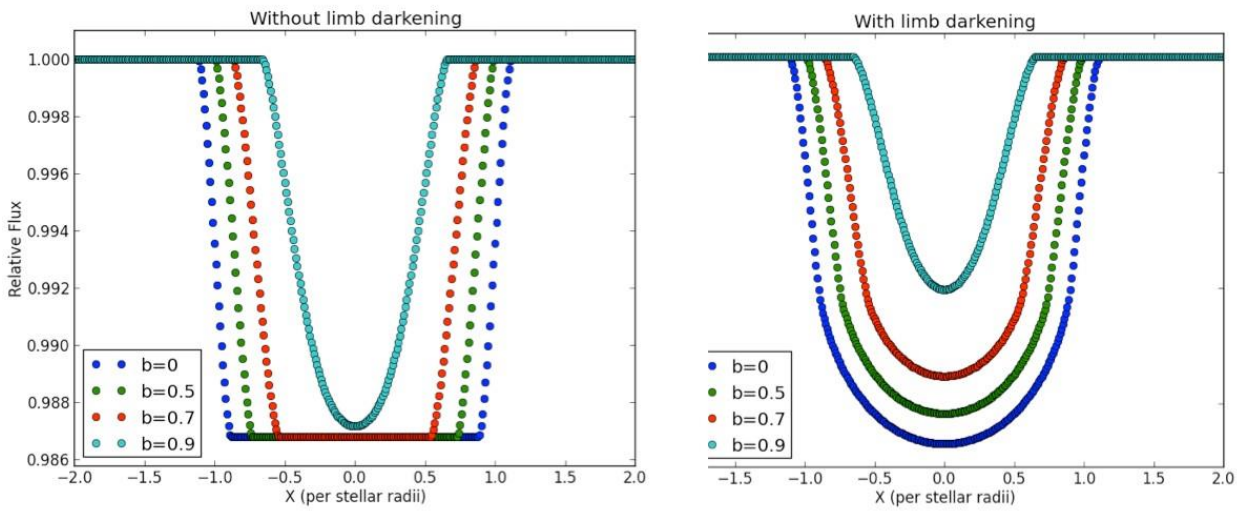

Figure 6: **(LEFT) Light curve of an exoplanet transit given different impact parameters (b), where b=0 corresponds to the eclipsing the central portion of the stellar disk. (RIGHT) Light curve of an exoplanet transit that includes the effects of limb darkening from its host star for differing impact parameters. Note the shape and relative flux of the light curves changes when modeling these two parameters. (Courtesy of planethunters.org).**

To determine very precise measurements of the exoplanet properties, astronomers must model the effects of limb darkening from the host star. As illustrated in Figure 6, the shape of the light curve is a function of the impact parameter as well as limb darkening from that particular host star (i.e., spectral type). There are a variety of analytic functions that exist for computing the effects of limb darkening, which all involve stellar atmosphere models. Simple limb darkening models assume a linear function where the intensity of the light observed is a function of the observing angle (θ) from the line of sight of the observer to that of the stellar disk,

$$\frac{I_\mu}{I_{\mu=1}} = 1 - c(1-\mu),$$

where μ = cos θ, and I(μ=1) is the intensity at the center of the star, and c is the limb darkening coefficient. More advanced models use higher order functions and even non-linear functions. The quadratic form of the limb darkening equation is,

$$\frac{I_\mu}{I_{\mu=1}} = 1 - c_1(1-\mu) - c_2(1-\mu)^2,$$

where c_1 and c_2 are the limb darkening coefficients.

For the purposes of this lab we will make use of the Mandel & Agol (2002) to genereate modeled light curves. Eric Agol at University of Washington has posted their code for public use. We will make use of the Python version that has been rewritten by Jason Eastman and use the quadratic form of the limb darkening law.

> **Light curve modeling code** (Click on the link "Python" in version 2.)
> https://faculty.washington.edu/agol/transit.html

Your team will need to download this code. There are four input parameters to this code: limb darkening coefficients (c_1 and c_2), normalized separation of the host star and plan (*z*), and ratio of the planet and star radius (*p*). The p parameter is the ratio of the radius of the planet and the radius of the star (R_p/R_*). The z parameter is illustrated in Figure 1, but you will need the time dependent z(t) as defined in Mandel & Agol (2002) for a circular orbit (e=0),

$$z(t) = \frac{a}{R_*}\sqrt{[(\sin\omega t)^2 + (\cos i \cos\omega t)^2},$$

Should be 2pi/period

where w is the orbital frequency (1/period) and t is the time measured with respect to the center of transit. The input of the Python code is the following,

```
# Python translation of IDL code.
# This routine computes the lightcurve for occultation of a
# quadratically limb-darkened source without microlensing.  Please
# cite Mandel & Agol (2002) and Eastman & Agol (2008) if you make use
# of this routine in your research.
def occultquad(z,u1,u2,p0):
.
.
.
```

returns limb darkening and uniform disk ratios

You will need to look up the properties of the host star from ETD and use transit properties you estimated in §7.1 to estimate z and p. For the limb darkening coefficients you will need to use Claret (2004) models of stellar atmosphere to determine the appropriate c_1 and c_2. You may use VizieR to determine the coefficients by inputting the effective temperature and surface gravity of the host star. (Assume a solar metallicity, log(M/H)=0). Be careful to match the estimated stellar properties with the grid scale of T_{eff} and log[g] in Claret (2004).

table9 is the right one

> **Limb darkening coefficients, use VizeR of Claret (2004**):
> http://vizier.cfa.harvard.edu/viz-bin/VizieR-3?-source=J/A%2bA/428/1001/table4

Input parameters into the Mandel & Agol (2002) model for each observational time (e.g., use fits header information per frame). This will give a predicted flux per time in the transit, and from this you can generate a model light curve. Compare this model light curve to that of your observations. How do they compare? How would you quantify the comparison and deviation from the fit? Describe the parameters used in this program and what gave the best fit to the observations.

8 References

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