Summer 2014

Astro 1 Lab Exercise

Lab #4: ExoPlanet Detection

Wednesday Aug 7, 8 and 11
Room 200 in Wilder

Lab reports are due by 5 pm on Friday August 15, 2013

Put it in the large ASTRO 1 Lab Box just inside the front door of Wilder. One (1) point will be deducted for every day your report is late.
Introduction

One of the most exciting new topics in the field of astronomy is extrasolar planets (or “exoplanets”). This Extrasolar Planets Lab is based on a lab developed by the University of Nebraska and involves the search for planets outside of our solar system using the Doppler and transit methods. It includes simulations of the observed radial velocities of singular planetary systems and introduces the concept of noise and detection.

This lab involves making observations of using simulated planetary radial velocity changes and planetary transits. This is lab is meant to give you an idea of how astronomers can take spectra and detect exosolar planets and how the NASA spacecraft Kepler is discovering new planets and planetary systems using the transit method. If you’re interested in keeping up with Kepler discoveries, go to: http://kepler.nasa.gov/

Also, it will help quite a bit if you READ THIS WHOLE HANDOUT before you come to lab
Part I: Exoplanet Radial Velocity Simulator

Open the exoplanet radial velocity simulator at:

http://astro.unl.edu/naap/esp/animations/radialVelocitySimulator.html

You should note that there are several distinct panels:

-- A **3D Visualization** panel in the upper left where you can see the star and the planet (magnified considerably). Note that the orange arrow labeled *earth view* shows the perspective from which we view the system. The **Visualization Controls** panel allows one to check *show multiple views*. This option expands the 3D Visualization panel so that it shows the system from three additional perspectives:

-- A **Radial Velocity Curve** panel in the upper right where you can see the graph of radial velocity versus phase for the system. The graph has *show theoretical curve* in default mode. A readout lists the **system period** and a cursor allows one to measure radial velocity and thus the **curve amplitude** (the maximum value of radial velocity) on the graph. The scale of the y-axis renormalizes as needed and the phase of perihelion (closest approach to the star) is assigned a phase of zero. Note that the vertical red bar indicates the phase of the system presently displayed in the 3D Visualization panel. This bar can be dragged and the system will update appropriately.
There are three panels which control system properties.

-- The **Star Properties** panel allows one to control the mass of the star. Note that the star is constrained to be on the main sequence – so the mass selection also determines the radius and temperature of the star.

-- The **Planet Properties** panel allows one to select the mass of the planet and the semi-major axis and eccentricity of the orbit.

-- The **System Orientation** panel controls the two perspective angles. **Inclination** is the angle between the Earth’s line of sight and the plane of the orbit. Thus, an inclination of 0º corresponds to looking directly down on the plane of the orbit and an inclination of 90º is viewing the orbit on edge.

-- **Longitude** is the angle between the line of sight and the long axis of an elliptical orbit. Thus, when eccentricity is zero, longitude will not be relevant.

There are also panels for **Animation Controls** (start/stop, speed, and phase) and **Presets** (preconfigured values of the system variables).
--- Exercises

Select the preset labeled Option A and click set. This will configure a system with the following parameters – inclination: 90°, longitude: 0°, star mass: 1.00 Msun, planet mass: 1.00 Mjup, semimajor axis: 1.00 AU, eccentricity: 0 (effectively Jupiter in the Earth’s orbit).

Question 1: Describe the radial velocity curve. What is its shape? What is its amplitude? What is the orbital period? ____________________________________________________________________________

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Now, increase the planet mass to 2.0 Mjup and note the effect on the system. Then increase the planet mass to 3.0 Mjup and note the effect on the system.

Question 2: In general, how does the amplitude of the radial velocity curve change when the mass of the planet is increased? Does the shape change? Explain. ____________________________________________________________________________

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Return the simulator to the values of Option A. Increase the mass of the star to 1.2 Msun and note the effect on the system. Now increase the star mass to 1.4 Msun and note the effect on the system.

**Question 3:** How is the amplitude of the radial velocity curve affected by increasing the star mass? Explain.______________________________________________________________
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Return the simulator to the values of Option A.

**Question 4:** How is the amplitude of the radial velocity curve affected by decreasing the semi-major axis of the planet’s orbit? How is the period of the system affected? Explain. ________________________________
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Return the simulator to the values of **Option A** so that we can explore the effects of system orientation. It is advantageous to check **show multiple views**. Note the appearance of the system in the **earth view** panel for an inclination of 90°.

Decrease the inclination to 75° and note the effect on the system. Continue decreasing inclination to 60° and then to 45°.

**Question 5:** In general, how does decreasing the orbital inclination affect the amplitude and shape of the radial velocity curve? Explain. 

Question 6: Assuming that systems with greater amplitude are easier to observe are we more likely to observe a system with an inclination near 0° or 90°. Explain.

Return the simulator to Option A. Note the value of the radial velocity curve amplitude. Increase the mass of the planet to 2 MJup and decrease the inclination to 30°. What is the value of the radial velocity curve amplitude? Can you find other values of inclination and planet mass that yield the same amplitude?
Select the preset labeled **HD 39091 b** and click **set**. Note that the radial velocity curve has a sharp peak.

**Question 7:** Determine the exact phase at which the maximum radial velocity occurs for HD 39091 b. Is this at perihelion? Does the minimum radial velocity occur at aphelion? Explain. (Hint: Using the **show multiple views** option may help you.) _____________________________________________________

This simulator has the capability to include noisy radial velocity measurements. What we call ‘noise’ in this simulator combines noise due to imperfections in the detector as well as natural variations and ambiguities in the signal. A star is a seething hot ball of gas and not a perfect light source, so there will always be some variation in the signal.

Select the preset labeled **Option A** and click **set** once again. Check **show simulated measurements**, set the noise to 3 m/s, and the number of observations to 50.

**Question 8:** The best ground-based radial velocity measurements have an uncertainty (noise) of about 3 m/s. Do you believe that the theoretical curve could be determined from the measurements in this case? (Advice: check and uncheck the **show theoretical curve** checkbox and ask yourself whether the curve could reasonably be inferred from the measurements.) Explain.

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Part II: Exoplanet Transit Simulator

Open the exoplanet transit simulator at:
http://astro.unl.edu/naap/esp/animations/transitSimulator.html

There are three panels which control system properties.

-- The **Star Properties** panel allows one to control the mass of the star. Note that the star is constrained to be on the main sequence – so the mass selection also determines the radius and temperature of the star.

-- The **Planet Properties** panel allows one to select the mass of the planet and the semi-major axis and eccentricity of the orbit.

-- The **System Orientation** panel controls the two perspective angles. Inclination is the angle between the Earth’s line of sight and the plane of the orbit. Thus, an inclination of 0° corresponds to looking directly down on the plane of the orbit and an inclination of 90° is viewing the orbit on edge. Longitude is the angle between the line of sight and the long axis of an elliptical orbit. Thus, when eccentricity is zero, longitude will not be relevant.

There are also panels for Animation Controls (start/stop, speed, and phase) and Presets (preconfigured values of the system variables).
The panel in the upper right shows the variations in the total amount of light received from the star. The visualization panel in the upper left shows what the star’s disc would look like from earth if we had a sufficiently powerful telescope.

The relative sizes of the star and planet are to scale in this simulator. Experiment with the controls until you are comfortable with their functionality.

**Step 1:**

In the preset box on the left, select Option A and then click “set”. This option configures the simulator for Jupiter in a circular orbit of 1 AU with an inclination of 90°. The number of data point should read 50. If not, hit the rest button at top right.

Click “on/off” the theoretical light curve and the simulated measurement data points to see how changing the level of noise and the number of data points makes the planet’s eclipse of the star’s light more or less visible.

**Question 9:** If the noise level is set at 0.10, is there any way to detect the planetary eclipse by increasing the number of data points? ____________________________________________

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**Question 10:** If the noise level is changed to 0.01, how does that affect detection of the planet? Now can you see the planet transit eclipse? ____________________________

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Step 2:

Now, still using Option A (Jupiter and the Sun-like star) decrease the noise level down to 0.001 and setting the number of data point to 200, one should see an obvious planetary eclipse. Change the phase by using the slider at the lower right to where the planet’s disk is just inside the star’s disk.

In the upper right plot of the eclipse data, a line shows the location of the eclipse phase.

**Question 11:** If you were shown just the light curve, could you pick out the moment where the planet moved completely inside the star’s disk? What happens at that point? _____________________________________________________________
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Step 3:

Now, keeping all the setting the same, switch to Option: OGLE-TR-113b.

**Question 12:** How did the light curve change? You can toggle back between this and Option A to check on differences? ______________________________________________________________________
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**Question 13:** Where on the light curve did the planet’s eclipse start?
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Step 4:

Now, switch to Option 2: B (with a tiny planet).

**Question 14:** If you wanted to detect this tiny planet, what noise and data point number would you need to get a secure and clear transit detection?

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Step 5:

Lastly, switch to Option 6: HD 209458 b

**Question 15:** With the noise level at its lowest setting (0.000010), what is the least number of data points that would map out the major parts of the eclipse; that is, from before the eclipse starts, the initial decline in light, then the steady eclipse portion, then back up to pre-eclipse levels and end of eclipse to pre-eclipse light levels.

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Part III: Real Transit Data

There are several computers attached to a photosensitive detector. This detector will measure the light from an artificial star projected onto a screen near the front of the room.

Once you have the computer turned on, click DataStudio to launch the software that will enable you to see the light the photosensor is detecting. Once the program starts, you should see a graph plotted on your computer screen.

Click on the green + symbol at the top left of the plot….this will enlarge the plotted region to fill much of the screen.

To start recording and plotting the measured light, click the start button at top left. You should then see data points being plotted on the graph. You can stop and re-start the graph at any time. You can also name the plot by clicking on the small graph symbol at the lower left hand side of the screen.
• You will need to stretch and move the x and y axes to allow you to better examine the sensor’s output.
• To stretch the x or y axis either bigger (enlarge) or smaller (shrink), move the cursor over the axis numbers and move left right or up and down.
• To shift the graph to the left or right (or up and down), move the cursor onto the solid axis line. A hand symbol appears which will then allow you to shift the plotted region so that you can see better the measured flux.
• Note: The sensor will continuously take measurements and these values will keep appearing on the right side of the plot. In order to see the latest numbers/values, you’ll need to keep adjusting the position of the x-axis region by means of the cursor on the x-axis solid line.
• Now adjust the graph region on the screen so as to have the data points show up near the top of the plotted region.

The TA will move four (4) artificial planets across the face of the star, simulating four transiting planets of varying sizes and transit durations.
Make printouts for each of the **four** planetary transits.

Make note of:

a) the time **each** planet takes to move completely across the star’s face,

b) the depth of the flux decrease (the x-axis is in seconds of time).

c) the “noise” of the detector when outside of a planetary transit.

• The sensor will continuously take measurements whether or not a planet is transiting the star.

• You can make a printout the the transit (once its over) of each planet by clicking the FILE button along the top left and clicking “print”. You can make prints of what you see on the screen at any time – even when taking data.

• For the smaller planet transits, you likely will need to adjust the position of the x-axis region by means of the cursor on the x-axis solid line and the stretch of the y-axis so as to better see and show the depth of these weak transits.
The maximum depth of a planet’s transit is an indication of the relative surface areas of the planet versus the star. For this lab, assume the star is like that of our Sun and hence has a radius of $7 \times 10^5$ km.

1) Thus, calculate the linear diameter of the planet using the equation for the surface AREA of a sphere $= 4\pi r^2$

so,

$$A_{\text{planet}} / A_{\text{star}} = \left( \frac{r_{\text{planet}}}{r_{\text{star}}} \right)^2 = \text{maximum fractional light decrease}$$

**Example:** In the case shown to the left, the drop was from 57.5 to 41.0 units. This represents a drop of 16.5 units. Subtracting a zero flux level reading of 1.0 done when the star was turned off means the planetary transit really represented a drop of $57.5 - 1.0 = 56.5$. Thus, a 16.0 unit drop is a decrease of 0.283 or roughly 28%.

The sq root of 0.283 is 0.53 meaning the planet has a radius just over half that of the star, i.e., a very big planet indeed!
2) The planet’s orbital speed can also be calculated if we assume the planet crosses over the very center of the star. Because the transit starts with the planet’s right-hand edge but ends with the planet’s left-hand edge, the transit time from start to finish is equal to the star’s diameter minus the planet’s diameter.

So, for example, from the previous step, once can calculate the distance traveled as: 
\[ \text{dia} = 2 \times \text{radius} = 14.0 \times 10^5 \text{ km} - 7.4 \times 10^5 \text{ km} = 6.6 \times 10^5 \text{ km} \]

Using the conversion of 1 sec = 1 hour, calculate the planet’s orbital velocity. If the observed transit time was 10 sec = 10 hours, then the planet’s orbital velocity is approximately:
\[ 6.6 \times 10^5 \text{ km/10 hrs} = 66,000 \text{ km/hr} = 18.3 \text{ km/s} \]
From this orbital velocity of 18.3 km/s, one can determine (assuming a strictly circular orbit) the planet’s distance from the star, d.

The equation comes from Newton’s law of gravity and is:

\[ V^2 = G \left( m_1 + m_2 \right) \times \left( \frac{1}{d} \right) \]

where \( m_1 \) is the mass of the Sun
and \( m_2 \) is the mass of the planet.

If we take the Sun’s mass to be much, much larger than that of the planet so it can be safely ignored, the equation then simplifies to become:

\[ V^2 = \left( G \ M_{\text{sun}} \right) \times \left( \frac{1}{d} \right) = \left( 6.67 \times 10^{-11} \text{ N m}^2/\text{kg}^2 \right) \left( 2 \times 10^{30} \text{ kg} \right) \left( \frac{1}{d} \right) \]

where \( d \) is in units of meters.

Converting 18.3 km/s to meters per sec => 18,300 m/s
so \( v^2 = 3.35 \times 10^8 \text{ m/s} \).

Finally, \( d = 4 \times 10^{11} \text{ m} = 4.0 \times 10^8 \text{ km} = 246 \text{ million miles} = 2.7 \text{ AU} \)
Using Kepler’s 3rd Law of planetary motion, $P^2 = a^3$ we can also calculate the expected period of the planet.

Since we are assuming the star is just like our Sun, the equation works straight away, so at a distance of $2.7 \text{ AU}$, the planet would have a period of:

$$P^2 = (2.7_{\text{AU}})^3 = 19.7$$

leading to a orbital period $P = 4.4 \text{ years}$.

Lastly, given the level of noise in the observed detector signal, estimate the smallest light decrease one could detect with a good deal of confidence using this lab set-up, and hence estimate the smallest size planet one could discovery using this equipment.

*** Calculations to do later***
What to include in your lab report

1. Both you and your partner's names.
2. Date and time you did this lab.
3. The name of the TA present.
4. Your answers to the 15 questions from Parts I and II
5. The four plotted graphs of the planetary transits
6. Then for each planet in Part III, list:
   1. The observed maximum decrease of light (fraction)
   2. The planet’s estimated diameter
   3. The planet’s estimated orbital velocity
   4. The planet’s estimated orbital parameters \( a \) and \( P \) in AUs and Earth years
7. An estimate of the smallest planet one can detect using this setup given the size and variability of the equipment noise level.
8. Your answers to the calculations (pages 16-19) following Part III.