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Exploring Transiting Extrasolar Planets in your Astronomy Lab, Classroom, or Public Presentation

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Abstract. The search for life beyond our Solar System is topic that appears in almost every introductory, general-education astronomy course, typically referred to as "Astro 101." School teachers and science museum presenters might cover this topic, too. This article is our instructor's manual for facilitating a 50-minute, hands-on activity that explores the light curves produced by transiting extrasolar planets: how they form and how to extract characteristics about the extrasolar planet from the shape of the curve. Students apply their skills to the system HD 209458 by examining data collected by the Microvariability Of STars (MOST) telescope.

1. Introduction

Before we find life beyond our Solar System, we must find places to look: extrasolar planets, that is, planets beyond ("extra-") our own Solar System. We have already found hundreds of them. A growing number of discoveries are being made by NASA's Kepler mission which uses the transit method to detect extrasolar planets. When a planet passes directly between us and its sun, the planet transits the star, and there is a periodic dip in the brightness of star as the planet blocks some starlight from reaching us. By decoding the star's light curve, we can uncover some of the characteristics of the planet: its orbital period and diameter and, if we know the mass of the star, the extrasolar planet's orbital radius. From these, we can determine if the extrasolar planet is in the habitable zone, the "Goldilocks" region around the star that is not too cold (and water is frozen) or too hot (and water is vaporized.) Around distant stars, just as it is on Mars, Europa, and Enceladus and here on Earth, our search for life is really a search for liquid water.

The search for life beyond our Solar System is topic that appears in almost every introductory, general-education astronomy course, typically referred to as "Astro 101." At the University of British Columbia, the 100 to 200 students in our Astro 101 class attend bi-weekly, 50-minute, hands-on activities in groups of 30 to 40. With the support of the Carl Wieman Science Education Initiative, we created activities for these sessions which (i) explore those course learning goals best-suited for hands-on experience (ii) employ, as much as possible, research-based instructional strategies. We also take the opportunity to teach and train our teaching assistants (TAs) about astronomy education by providing them with a detailed "TA Guide" for each activity. These guides are not simply a list of equipment and materials and a recipe of steps for running the activity.

Rather, we justify why each step in the activity occurs, alert the TAs about what to expect, and give samples of dialogue the TAs can use to drive the activity forward.

In Section 2, we reproduce the "TA Guide" for the extrasolar planets activity. In Section 3, we give some suggestions for presenting this concept in other settings: in the lecture hall as an interactive demo and in a science centre, museum or other public presentation. All materials mentioned here, including all the hand-outs, the poster of the HD 209458 lightcurve, and the LoggerPro file "LightCurve.cmbl" are available online.[1]

2. TA Guide

This section reproduces the TA guide for the transiting extrasolar planets activity. The guide is written in 2nd-person ("Place your hand in front of the light sensor...") to better connect with the TA preparing to facilitate the activity. Our suggestions for dialogue the TAs can use to lead the activity *are written in italics*.

Description

In this 50-minute tutorial, students discover how to interpret the light curves of stars with transiting extrasolar planets and how to extract characteristics of the planet. They apply these techniques to the real planet HD 209458b. In order to get there, students first explore how light curves form (Part 1) and then what a light curve reveals qualitatively (Part 2) and quantitatively (Part 3) about extrasolar planets.

Learning Goals

By the end of the tutorial, a student should be able to

- illustrate how extrasolar planets are detected and extract properties of the planets and stars from the observations, and
- compare extrasolar planets to our own.

Preparation

There is a lot of equipment to get set up for this tutorial.

1. Computer (hooked up to a digital projector) with
    - LoggerPro program
    - LoggerPro file LightCurve.cmbl. When you close the program at the end of the tutorial, it will likely ask you if you want to save the changes. Click No. If you accidentally save a changed version of the file, there is a backup copy on the computer's desktop.
    - PDF of hand-outs open in a PDF reader like Acrobat
2. Light sensor (Vernier LS-BTA photometer) plugged into Go!Link plugged into a USB port on the computer. The sensor is inside a white tube of paper, coloured black inside, which reduces the amount of scattered light hitting the sensor.

[1] PDF and source files are available at `blogs.ubc.ca/polarisdotca/astrolabs`.

Figure 1. The Vernier light sensor is inside a tube of paper to block scattered light. The sensor connects through a Go!Link interface to the computer USB port.

3. Equipment stand with clamp for holding the light meter.
4. One small and one large styrofoam ball planets. Ideally, the large one has exactly twice the diameter of the small one.
5. White globe lamp.

Figure 2. A globe lamp is mounted on a wooden block. Demonstrators pass styrofoam "planets," held at the ends of pencils, in front of the "star" to simulate a transit.

6. Poster of HD 209458 light curve taped to the wall. Data were collected by the Microvariability and Oscillations of STars (MOST) telescope, a Canadian space telescope operated from the University of British Columbia.
7. Hand-outs for the students:
   - Pages 1–3, single-sided, one for each group.

- Page 4 (Questions), one for each student.

Set up the computer cart at the front of the room. Clamp the light sensor into the equipment stand at the height of the middle of the globe lamp. Place it about 1 metre from the globe lamp and aim it at the center of the lamp. Set up the projector (on the overhead cart) so it shines on the screen next to the globe lamp. The goal is to make it possible for the students to simultaneously see the globe lamp, the transiting planets and the LoggerPro graph projected onto the screen, without the light sensor picking up too much light reflected off the projector screen. The diagram below shows one possible configuration.

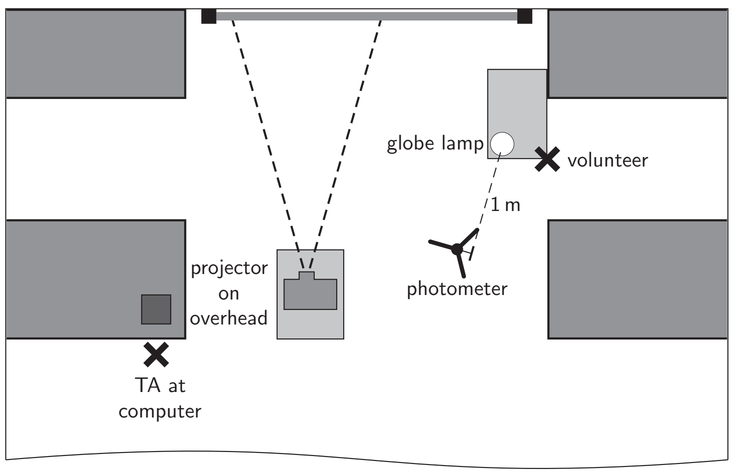

Figure 3. Configure the room so students can simultaneously see the transiting planet and the projected light curve.

Boot the computer, plug in the Go!Link USB cable and double-click the LoggerPro file "LightCurve" on the computer desktop. After it initializes, the LoggerPro window should recognize the light sensor and begin collecting measurements (look for the lux readings at the top-left of the LoggerPro window). Click the green Start (and red Stop) button to start graphing the brightness of the globe. The graph cycles every 20 seconds, so once you've pressed Start, you can just let it continue.

The readings might be "ragged." If it's bad, try moving the light sensor so it receives less light scattered off the screen from the projector. The paper tube, coloured black inside, reduces the scattered light, though it has to be more carefully aimed at the globe light. If there are fluorescent lights in the room, those can also mess up the readings if the data is collected at 50–60 Hz. It's surprisingly sensitive. Experiment with the sampling rate (Ctrl-D in LoggerPro) to find a rate that reduces that interference. In the end, it's okay if the readings are a bit ragged: it makes it look more like the HD 209458 observations the students will see shortly.

Don't start collecting data and plotting the curve, though. That will be too distracting for your introduction. Instead, project the top of Page 1 of the hand-outs. It will encourage the students to read Page 1 when you give it to each group. We want the students to discover for themselves what characteristics of the transiting planet are important, so *don't* hand-out Pages 2 and 3 of the worksheets (listing characteristics that matter) since that will short-circuit the discovery stage.

Part 1a: Introduction to Extrasolar Planets (5 minutes)

This section provides some background and get the students "up to speed" in case the instructor hasn't covered extrasolar planets yet. With all the new Kepler results, check `planetquest.jpl.nasa.gov` for the latest number of confirmed extrasolar planets. You can use that number in the intro:

> *Astronomers have discovered hundreds (or use actual* `planetquest` *number) of planets orbiting other stars. These are planets and stars outside our Solar System, so we call them extrasolar planets.*
>
> *There are 3 main methods for finding extrasolar planets:*

Radial velocity (Doppler) method: *When a planet orbits a star, the star wobbles back and forth a small amount as it (and the planet) orbit around the center of mass. [Pick up the globe lamp and swing it around in a small circle towards and away from the students.] The star light is redshifted and blueshifted as the star moves away or towards us. By detecting these periodic Doppler shifts, we know a planet is there.*

Direct detection: *A very small number of extrasolar planets have been observed directly. This is very difficult because planets are small and stars are so bright. If the globe lamp is our Sun, then Earth is about 1 mm in diameter, 10 metres away. That is very hard to see.*

Transit method: *When an extrasolar planet crosses ("transits") directly between us and the star, it temporarily blocks some of the star light and the star's brightness dips. In this tutorial, we'll explore this transit method. [Be sure to define and emphasize the word "transit" so that when the students see "transit method" in the future, they know it's about dips in the light curves.]*

Part 1b: Observations (5–10 minutes)

Ask for a volunteer ("John") to come to the front to move the planets—warn John to be careful with all the cords. Explain we're pretending the globe lamp is a star that we're observing with our telescope, the light sensor. Switch the projection to the LoggerPro window and click Start to begin plotting the light curve. Reading and interpreting graphs is another skill we're teaching—they are not experts—so be sure to orient the students to what the graph shows:

> *The horizontal axis is time. The vertical axis is intensity or brightness of the star. The graph, called a light curve, it tracks how much light the sensor is receiving.*

Put your hand in front of the light sensor to demonstrate how the curve dips when you block some light.

Ask John to use the small planet first, moving the planet horizontally around the globe lamp like a planet orbiting its star. Encourage the rest of the students to try to record what they observe in the Observations table on Page 1. Encourage the students to ask the volunteer try things. If they're hesitant at first, you can suggest the volunteer do a slow transit followed by a fast one so that both dips are visible on the graph. You might want to "freeze" the light curve by clicking Stop in the LoggerPro window. Ask the students what the difference is in the shapes of the curves and what that tells us about the planet. Then click Start to continue watching for patterns.

Ask John to switch to the big planet ("John, could you hold up the big planet for the class to see?"). Before he does the transit, get the students to make a prediction about what the dip will look like:

> *John is about to use a planet that's twice as big. Do you think the dip will be deeper or shallower? "Deeper!"*
> *Deeper, good. How much deeper? "2 times deeper!"*
> *[This is common mistake. Don't let them know it's wrong, though.]*
> *Good prediction, let's try. John, go ahead...*

Certainly the dip is deeper, but how much? Ask John to use both planets: two transits with the big planet followed by two transits with the small planet. Get him to start when the graph cycles so you can get all four dips on the same plot. Press STOP to freeze the plot after the four dips.

> *You can see the dips are deeper for the big planet. How much deeper? Let's measure...*

Use a ruler to measure the depth of the dip. It's quite easy to measure the curve right on the projector screen. The "100% illumination" line might not be horizontal in the light curve so measure the depth from just before it starts to drop or at the middle of the dip. Measure both deep dips and both shallow dips—they should be in a 4:1 ratio!

> *Hmm, it's not two times deeper, it's four times deeper. Why is that? Right, because the big planet's AREA is four times bigger.*

Most students incorrectly predict the dip will be two times deeper but once they see the demonstration and recognize that it depends on area, they usually have no trouble adjusting. However, it's important to emphasize the "squared" relationship between the depth of the dip and the diameter of the extrasolar planet because it comes up again in the activity and in the Questions at the end.

Part 2: Characteristics of Light Curves (10 minutes)

The next Part of the tutorial is for the students to make the links between the changes in the light curve and the characteristics of the transiting planet. Hand-out Page 2. Invite the students to complete the sheet:

> *Exactly how planets in a solar system orbit the star and block its light can be very complicated. A very good approximation, though, depends on only* ***two characteristics****: the diameter of the planet relative to the star and the length of time it takes the planet to orbit the star. Look at the light curves on Page 2 and figure out what they tell you about the planets.*

After about 5 minutes, or sooner if their attention starts to drift, project Page 2 of the hand-outs. Go over the answers stressing first, how the light curve changed and second, what that tells us about the planet:

> ***Planets A and B:*** *The dip is deeper in B indicating the planet has a larger diameter. How much larger? Two times because the dip is four times deeper.*
>
> ***Planets C and D:*** *The dips in D occur twice as far apart compared to C. Planet D takes twice as long as Planet C to orbit the star.*

Part 3: Decoding the Light Curve (15 minutes)

Hand out Part 3 and project it on the screen. Explain that we want to get *quantitative* values for a transiting planet's period and size, not just *qualitative* (or relative) values. Briefly go over the "tools" to find the period and diameter, reinforcing that the depth of the dip depends on the *area* of the planet compared to the area of the star, and those areas depend on the *squares of the diameters*.

The students will use these tools to learn about an actual extrasolar planet. Ask the students to take their worksheet and a pencil to look at the light curve for HD 209458. The big horizontal tick marks on the lightcurve are days; the small crosses are in 1-hour intervals. The large vertical ticks are 1% drops in intensity. They must *measure two quantities*: the period P and the depth of the dip ΔI. Ask them to be careful not to write on the poster.

Wander around the room and help with the calculations. If they don't have a calculator or phone capable of doing the calculations, they can always use google. The results are something like this:

Orbital period	Planet diameter
Measure the time between dips:	Measure the depth of dip:
$P = 3$ days, 12 hours	$\Delta I = 2\%$
Write the orbital period in days:	Convert % drop to a decimal (for example, 1% = 0.01)
$P = 3.5$ days	$\Delta I = 0.02$
and years	Find the ratio of diameters:
$P = 0.0096$ years	$\frac{d}{D} = \sqrt{\Delta I} = \sqrt{0.02} = 0.14$
	The star HD 209458 has diameter $D = 1,400,000$ km, the same size as our Sun. Find diameter d in km:
	$d = (0.14)(1,400,000) = 196,000\,\text{km}$

Part 4: Questions (Remainder of tutorial)

As students finish the calculations in Part 3, give them the Questions sheet, one per student. They can collaborate but we want the students to hand in their own papers. Here are some answers and comments:

1. We can use the simplified $a^3 = P^2$ version of Kepler's Law because the star HD 209458 has the same mass as our Sun ($M = 1$ solar mass). With $P = 3.5$ days or 0.0096 years, $a = \sqrt[3]{0.0096^2} = 0.045$ AU.

   The characteristics typically extracted by the students are remarkably close to those published for HD 209458b (Miller-Ricci et al. 2008):

period	$P = 3.52474832 \pm 0.00000029$ days
diameter	$D = 191,500 \pm 5700$ km
semi-major axis	$a = 0.045$ AU

2. The extrasolar planet has a size like Jupiter but an orbit far inside Mercury's.

3. Planets in the habitable zone of stars like our Sun take one year to orbit. It takes at least two to three years for the planet to make three transits. We need three dips to make sure: the first could be a random dip. The second dip suggests there a planet in orbit though it could be two planets of similar size. The third dip is strong evidence there is one extrasolar planet in orbit.

   If students are curious, ask them to imagine what the light curve of Earth transiting the Sun would look like to astronomers on HD 209458b: The Earth's diameter is about 100 times smaller than the Sun's so the dip in the intensity would be about $(0.01)^2 = 0.0001$ or 0.01%. That tiny dip is 20 times smaller than the "noise" in the HD 209458 lightcurve (about 0.2%) and occurs only once per year. Imagine trying to find a planet like Earth on the poster!

4. In the past, students have quite easily recognized the 4-day and 7-day periods (notice there are multiple choice answers with 2-day and 3-day periods: that's the number of dips, not the periods.) The key to choosing the right choice is remembering the dip is proportional to the square of the diameters. The 7-day dips are four times deeper which means Planet 2's diameter is two times bigger, not four times bigger.

Clean-up

The computer and other equipment must be locked up in the storage room. Return the digital projector to the Main Office.

3. In-class demonstrations and science center presentations

For Astro 101 courses without a lab, we also have a version of this extrasolar planets activity that runs as an in-class demonstration. It could easily be adapted to a presentation at a science center or a public outreach event.

We set up the equipment at the front of the room. The LoggerPro output is projected onto the screen so the audience can simultaneously see both the equipment and the light curve. Each participant receives a handout.

A volunteer comes up and makes a few orbits of the star using the big planet. With this practice, we get the volunteer ("John") to make a few nice, steady orbits. Then we ask the participants to make a prediction:

> *Have a look at your worksheet. Suppose the orbits John just made are represented by the light curve at the top. Now John is going to make the planet orbit twice as fast, that is, with half the period. What will the new curve look like? Pick one of the graphs A–D in Question 1.*

Students make predictions with clickers, ABCD-cards or a show-of-hands (or fingers). Students typically have no problem recognizing there would be twice as many dips in the light curve but many do not anticipate the dip being narrower like it is in the correct choice A because the planet transits the star in only half the time. With the prediction made, John goes ahead and makes the quick orbits. Having made predictions, the students are more likely to focus on the critical features of the graph: the period of the dips and their width.

Next, we switch to the small planet:

> *(John, would you grab the small planet, please? Thanks.) John is going to try this small planet. Its diameter is one half of the first planet. He's going back to the original, slower orbit. Which light curve in Question 2, A, B, C or D, do you think it will make?*

After making their predictions, John goes ahead and makes the orbits. The dips are definitely shallower. How much shallower, though? With the LoggerPro software, the instructor can measure the depth of the dips. Sure enough, the big dip was four times deeper.

There are lots of directions to go from there, including analyzing the MOST data for HD 209458, deducing orbital radius via Kepler's Laws and exploring the habitable zone.

4. Conclusions

The discovery of extrasolar planets is a story that appears daily in the media. It has grabbed the public's attention. Astro 101 students and science center attendees familiar with extrasolar planets, particularly the ones discovered by the transit method used by the Kepler mission, will have an opportunity to share their new-found knowledge with their community. More importantly, these people will contribute to building a more scientifically-literate society.

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References

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