Dear Teacher,

You are about to involve your students in one of the most exciting frontiers of science – the search for other worlds—and life— in solar systems beyond our own! Using the MicroObservatory telescopes, built and maintained by the Harvard-Smithsonian Center for Astrophysics and located at the Whipple Observatory in Amado, Arizona, students will gather real data to see if they can detect actual alien worlds orbiting distant stars. Welcome to the Laboratory for the Study of Exoplanets (aka “ExoLab’’!)

GETTING STARTED

Web Browser with Flash Plug-In. This project is entirely Web-based. Students can work individually or in groups, but they will need access to a computer with a standard Web browser with the Flash plug-in. Most browsers already come with the Flash plug-in installed. If you can’t see the labs when you click GO TO THE LAB, simply download Flash [here](#). NOTE: We have discovered compatibility issues with some versions of Internet Explorer. For best results, use Chrome, Firefox, or Safari web browsers.

Sign Up For a Classroom Account. Click the SIGN UP button at the top right of any ExoLab page and follow the instructions to provide your school and class information, and then set up a Teacher username and password that you will use to access your classroom account. (For each class you want to engage in ExoLab, you will need to sign up for a separate classroom account, so you may want to number your usernames, e.g. MrsJones1; MrsJones2, etc). Once you submit your school and class information, our ExoLab Team will review the request and you will receive an email within 2 days when your account is approved. The classroom account allows you and each of your students to take telescope images, and to store and retrieve individually personalized data and work from the project's database.

Logging In and Registering Students. Once you have received your approval email, you will use the Teacher username and password you signed up with to LOG IN to the ExoLab from any page and then click on REGISTER to set up each of your students with a unique username and password. (Save the account approval email, which will have more detailed instructions on registering your students).

Online Student Database. When they are logged in, each student’s account saves all their written comments, hypotheses, and answers to challenge questions within each Lab. Once they answer a question, it will automatically be saved to their account. Currently students can overwrite their answers and the journal will save only their most recent work.

Reviewing student’s work. Because you as the teacher sets up and manages your students’ usernames and passwords, you may review their work by logging in as each student and viewing their “My Results” pages. (Alternatively, you may ask students to take screen shots of
those aspects of the Lab you want them to hand in to you.) We are working on a feature to allow you to download a spreadsheet of student responses, but that is not currently available.

Additional Support for Teachers. The “For Teachers” link on the ExoLab home page contains additional materials, including the full Teachers’ Guide, and a link to ExoLab Video Tutorials on YouTube.

SCHEDULING THE PROJECT

Time Required. This project requires 5 to 10 regular classroom periods (although some teachers have had students investigate multiple target stars to extend the project). You can start the ExoLab at any time, since there are exoplanets observable on practically every night of the year. For future planning, calendars of upcoming ExoPlanet targets are on the Teachers section of the ExoLab website, and get updated every couple months. IMPORTANT: Do the project once yourself first before engaging students! The ExoLab is real science, including all the unexpected turns that an authentic investigation may take. You’ll be much better prepared to support your students if you experience the process of analyzing telescope image data yourself first.

Images Expire! Once you take your telescope images, they will only remain accessible from the Website for 4 weeks. (Student work - including measurements, graphs and written comments - remains on the Website without expiring.)

Plan for Clouds. Be aware, it may be cloudy when you take your images. If so, simply use the telescope again on another night. You may want to take images for several ExoPlanet targets during the week you begin, to raise the probability of getting good data.

Unlimited Access. There is no limit to the number of times you can access the telescopes, and no limit to the number of images you can take. (But remember, each image will be deleted from our server 4 weeks after you take it.)

WHY THIS PROJECT?

Engages Students in Frontier Science. The ExoLab Project engages students in the exciting scientific search to answer the age-old human question: Are we alone in the Universe? Central to the search for extraterrestrial life is the hunt for other Earth-like planets. Since the first extrasolar planet was discovered in the 1990s, new planets have been detected at an accelerating pace. Most of those discovered to date are much larger than Earth, closer to their stars, and therefore fiery, uninhabitable places. However, scientists expect to find more and more Earth-like worlds, orbiting just the right distance from their star, in the very near future. That means it is highly likely that this generation will be the first to find life beyond Earth.
Supports Next-Generation Science Standards.
The ExoLab Project aims to create a model for how to integrate content learning with the practices of authentic scientific study. The project is designed to work in a variety of physics, astronomy, and earth science classrooms. To a significant extent, you will decide your students’ specific learning objectives based on the content you intend to teach. However, all students should be able to develop and consolidate their knowledge and skills in the following NGSS-recommended areas:

<table>
<thead>
<tr>
<th>NGSS Disciplinary Core Ideas explored in ExoLab (Earth Science; Physical Science)</th>
<th>ExoLab students engage in these Scientific Practices</th>
<th>Cross-cutting Concepts encountered that apply across science domains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth’s Place in the Universe (ESS1.A &amp; B) Electromagnetic Radiation (PS4.B) Information Technologies and Instrumentation (PS4.C)</td>
<td>Asking questions Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics, information and computer technology, and computational thinking Constructing explanations Obtaining, evaluating and communicating information</td>
<td>Size, scale, &amp; proportion Systems and system models Patterns Cause and Effect</td>
</tr>
</tbody>
</table>

Fosters Data Literacy. The ExoLab is the real thing: the data that students collect are real, not canned. This means that students will learn to deal with the messiness of real data, and use the same kinds of analytical methods that professional scientists use every day to separate the signal from the noise in their investigations.

EXOLAB SEQUENCE OF ACTIVITIES
The core activities are outlined as follows:

Activity 1- Introduction & Welcome to the Laboratory for the Study of ExoPlanets
Welcome students to the community of planet hunters. Students explore the ExoLab website and share their ideas about the search for extraterrestrial life on other worlds

Activity 2 - Modeling Lab
Using a computer model, students predict the light curve of a star with an orbiting planet and consider how this model might inform their interpretation of their observational data.

Activity 3 – Telescope Lab
Students take images of stars known to have transiting exoplanets with the MicroObservatory telescope. Image requests should be made during the day before each night’s scheduled Exoplanet target observations

Activity 4 – Image Lab
Students take measurements of the relative brightness of their star to create a light curve, and examine the factors that may affect the quality of their telescope image data.
Activity 5 – Data Lab
Students analyze the light curve using a “best fit” model to figure out the size of the planet and the nature of its orbit. Along the way they use methods for identifying a signal within noisy data, and consider how to use statistics and a modeling tool to draw conclusions from a light curve with considerable scatter.

Activity 6 — Community
This page on the ExoLab website allows students and teachers to post their own work, and to see the work of other schools participating in the project.

TBD – Visualization Lab
In this Lab to be developed in the future, students will use all of the data they have collected to describe what they have learned about their planet. Then using an interactive computer-modeling tool, students will create a visualization of their planet.

TBD – Color Lab
This Lab, to be developed in the future, will enable students to engage in the characterization of extrasolar planets. Having now discovered thousands of exoplanets, researchers at this scientific frontier seek to glean the chemical and physical properties of these worlds, using spectroscopy to look for biosignatures.

Assessment
There are a number of opportunities throughout this project to assess students’ progress. Embedded in the project are several products, which are recorded in the students’ online account and can be assessed. Students are asked to make and test predictions using models and transit data they have collected and to explain their answers. Students are also asked to do mathematical calculations, the accuracy of which can be assessed. As a final assessment, you may wish to ask students to prepare a presentation, poster, or article describing their investigation. Try having them follow this typical format for scientific papers:

- Title—the subject and what aspect of the subject was studied.
- Abstract—summary of paper: The purpose of the investigation, the primary results, the main conclusions
- Introduction—why the study was undertaken, background
- Methods—how the study was undertaken
- Results—what was found
- Discussion—why these results could be significant (what the reasons might be for the patterns found or not found)

They may use screen shots from the ExoLab to illustrate their methods, data, etc.

BACKGROUND SCIENCE
Detecting extrasolar planets via the “transit method”
Astronomers have been hunting for planets that orbit stars similar to our own Sun. To date, they have confirmed detections of nearly 2000 of these new worlds (for the latest numbers,
go to [http://planetquest.jpl.nasa.gov/](http://planetquest.jpl.nasa.gov/). Only in very rare circumstances can astronomers use current telescopes to detect these planets directly. Instead, astronomers use indirect methods. One such method, used here in the ExoLab, involves detecting a planetary transit.

In a few cases, the orbit of an alien planet happens to be oriented so that the planet passes through our line of sight with the star. That is, the planet eclipses, or blocks, part of the star’s light; once during each orbit. These are called transiting planets, because if we were closer we would see the planet transit across the face of the star.

**How can a telescope be used to detect planetary transits?**

Telescopes do more than take pictures – they gather light; and the images contain valuable information about the amount of light reaching the telescope from each star. It turns out that even a small telescope, such as the MicroObservatory telescope students will be using, is sensitive enough to detect a 2-3% drop in the amount of light reaching the telescope when the image is taken. To detect a transiting planet, you must take a series of images that span the timeframe of the entire transit; measure the brightness of the star in each of those images; plot it on a graph of time versus brightness; and look for the telltale dip in brightness that is the signal of the alien world.
Activity 1 - Welcome to the Laboratory for the Study of ExoPlanets

PURPOSE. Use your first session as an opportunity to:

- **Introduce** students to the ExoLab website and the tools and activities they will be pursuing.
- **Engage** students in a preliminary discussion of this exciting frontier of science
- **Elicit** student knowledge and prior ideas about stars, planets, and the possibility of extraterrestrial life.

NGSS EDUCATIONAL OBJECTIVES. To introduce students to the project, it is important to give them time to consider their existing personal knowledge and their own questions about the universe beyond Earth, and think about why it might be interesting to look for other worlds. Throughout the ExoLab, students will have opportunities to demonstrate their understanding of the NGSS Disciplinary Core Ideas associated with:

- **Earth’s place in the Universe**, including ideas about the Universe and Its Stars, and about Earth and the Solar System.

Core Concept Underpinning this Lesson: Our Sun is a star, and the stars are suns. Even the nearest star lies enormously far beyond our own solar system. Stars are orbited by planets, which may be very different worlds from ours.

SUGGESTIONS FOR LEADING THE LESSON. Welcome students to the community of planet hunters. Let them know they will be making their own observations of recently discovered extrasolar planets, using a robotic telescope owned by the Harvard-Smithsonian Center for Astrophysics, and located at the Center’s Whipple Observatory in Arizona. The ExoLab website was designed by scientists and educators at the Center for Astrophysics, to provide students with access to the same kinds of instrumentation and analysis tools that the professionals use in this cutting-edge field of science. The students’ goal is to see if they can first, *detect* the signal of a planet in their observed star system, and then *analyze* the signal to draw evidence-based conclusions about the planet’s size, distance from its star, and orbital tilt.

Provide students with the usernames and passwords you set up for them, and once they log in, students can explore the website. (Students will know they are logged in when they see the upper right button change to “LOGOUT”). First, have them click on the “Overview” section from
the home page, and click through the Overview slideshow. Through a class discussion, have them express their ideas about the search for extraterrestrial life on other worlds. Here are some suggested thought questions for students; you may have some of your own.

**Student Questions:**

Most of the other solar systems discovered so far are not like our own. For a moment, travel in your imagination to an alien world. Describe what you think life might be like on:

a. A planet with one side that always faces its star.

*Students should realize that this would make one side very hot all the time, and the other side very cold. They should also realize that it would be permanent day on one side of the planet and permanent night on the other. Have them think about whether there might be any parts of this planet that might have conditions conducive to life.*

b. A rocky planet much bigger than Earth, where there’s more space on the surface and where gravity is stronger.

*Students might think about this question from a personal/human perspective, and imagine what it would be like to have more space for people to live, or for them to be heavier and for movements to be more difficult. They might also take a broader perspective and think about how life evolving on a planet with more gravity might look different from life on Earth.*

c. A much smaller rocky planet, where you’d have less space on the surface and weigh very little.

*Students’ answers will vary depending on whether they are thinking about this from a human perspective or from the broader perspective of potential impacts on the evolution of life. They might think about the ease with which they could move about, or about increased competition for space on this smaller world.*

d. A planet that is always cloudy, and there is never a clear day or night.

*Students might wonder if there would be enough light on the surface to support life. From a human perspective, people on the surface would never have seen the stars.*

e. A planet with a very eccentric orbit, so that for part of the year it is extremely close to the sun and part of the year it is very far away.

*This question is a good opportunity to review students’ understanding of the cause of Earth’s seasons. Earth’s seasons are caused by the planet’s tilt (the orbit around the Sun is nearly round and the Earth is actually closer to the Sun during the Northern Hemisphere winter). In this*
example, the very eccentric orbit would cause extreme temperature differences from one part of the year to another.

You may wish to go over the size and scale of planets in our own Solar System so that your students have this in their mind as they look at other planetary systems. Some teachers also like to start this project by having their students examine a physical model of a transiting planet system – e.g., a light bulb with a small ball on a stick orbiting around it. In the next “Modeling Lab” session; students will work with an online visual model of the kinds of systems they will be investigating.

Important Note for Teachers: Depending on your scheduling and the exoplanet transit calendar (on the Teachers page), you may wish to use your teacher account to request images for a few nights leading up to the date on which your students are ready to use the telescope. This will increase the chances that there will be a good set of images in your class account for at least one exoplanet target when your students are ready to reduce data. Remember, cloudy nights are the foil of all astronomers!
Activity 2 – MODELING LAB

PURPOSE. This activity sets up the rest of the ExoLab investigation, and is intended to help your students predict what the “signal” of an alien world might look like. They use the model to:

- **Visualize** an alien solar system oriented so that a planetary transit takes place.
- **Plan** their investigation [which involves obtaining a series of star brightness measurements over time]
- **Predict** how a graph of the star’s brightness versus time (a light-curve) can be used to:
  - provide evidence that they have detected a planet, and
  - quantitatively determine the size of the planet compared its star

NGSS EDUCATIONAL OBJECTIVES. This lab gives students experience with the following scientific practices, while they apply and consolidate their disciplinary core understandings of what makes a solar system a system:

- **Reasoning from a model**, including using the Cross-Cutting Concept of Size, Scale, and Proportion to understand how the size of an exoplanet influences the proportion of starlight blocked during a transit.
- **Translating** from one representation of a system (the visual model) to another representation (a graph of brightness vs. time).

Students will use this predictive model later on to help them interpret their findings with the telescopes.

**Core Concept Underpinning this Lesson:**
Models are important tools used by scientists working at the frontiers of science. A model – physical, visual, or theoretical – captures important features of the world, and helps us analyze and predict its behavior. It’s important to evaluate both the merits and limitations of a model in using it to make predictions or interpret real data.

BACKGROUND SCIENCE
Detecting extrasolar planets via the “transit method”
Astronomers have been hunting for planets that orbit stars similar to our own Sun. To date, they have confirmed detections of nearly 2000 of these new worlds, with 3000 more good candidates awaiting confirmation by further observation and analysis (for the latest numbers, go to planetquest.jpl.nasa.gov). Because planets do not shine with visible light of their own, and are so dim and small compared to the stars they orbit, it is only in very rare circumstances can astronomers use current telescopes to detect these planets directly. Instead, they primarily use indirect methods. One such method, used here in the ExoLab, involves detecting a planetary
transit.

In a few cases, the orbit of an alien planet happens to be oriented so that the planet passes through our line of sight with the star. That is, the planet eclipses, or blocks, part of the star’s light once during each orbit. These are called transiting planets, because if we were closer we would see the planet transit across the face of the star.

**How can a telescope be used to detect planetary transits?**

Telescopes do more than take pictures – their electronic detectors gather light; and the digital images derived from this electronic data contain valuable information about the amount of light reaching the telescope from each star. It turns out that even a small telescope, such as the MicroObservatory telescope students will be using, is sensitive enough to detect a 2-3% drop in the amount of light reaching the telescope when the image is taken. In fact, many of large exoplanets students will be observing were originally discovered by small telescopes similar to the ones they use in the ExoLab. To detect a transiting planet, you must take a series of images that span the timeframe of the entire transit; measure the brightness of the star in each of those images; plot it on a graph of time versus brightness; and look for the telltale dip in brightness that is the signal of the alien world.

**SUGGESTIONS FOR LEADING THE LESSON.**

If you haven’t already, you may wish to begin this lesson with a discussion of student’s own ideas about what methods astronomers might use to detect planets around other stars. Some teachers may want to first use a physical model (a ball and light bulb) to demonstrate the “transit method.” (A nice review of detection methods can be found at this URL: [http://planetquest.jpl.nasa.gov/page/methods](http://planetquest.jpl.nasa.gov/page/methods))

In the online Modeling Lab, student will use a computer-based model of a solar system to predict how the brightness of their star varies as a planet transits across (eclipses) the star. Later, after they have made their actual observations, they will use the same model to interpret specific features of their data that reveal what their alien solar system might look like.

Remind students that we can’t see an alien world directly, but we can see its effect on light from the star that it orbits. As students interact with the Modeling Lab, they should use the numbered buttons to consider the model in 6 stages.

---

**Starting with Stages 1 and 2,** the text at the bottom of the Lab provides instructions and tips for thinking about how the Modeling Lab can help students interpret the results of their investigation. (They may want to put their web browser in “Presentation” mode to be able to see more of the Lab screen at once).
Stage 3 asks students to make a graphical prediction of what the star’s brightness over time would look like, and then to enter a verbal explanation describing at least 3 feature of their graph that relate to the model. Point out that they can pause and restart the movement of the planet in this model. Students should be sure to click “Save Graph” and “Save Work” and check the “Status” bar to insure that their graph and text gets saved to their ExoLab account.

MODELING LAB Stage 3: You can have students save a screen shot, like the one above, to hand in to you for assessment

After your students have completed and saved their Stage 3 work on their own, you may wish to facilitate a class discussion about how the details of a light-curve graph match (or provide evidence for) the visual model. Gaining fluency in going back and forth between a graphical and visual model is an important scientific skill, and there are many nuances to the model that your
Stage 4—Use Math to Predict. This stage asks students to think quantitatively about how the amount (percentage) of dimming in the star’s brightness is related to the size of the transiting planet.

MATH ALERT! Most students will naively assume a direct proportion between the linear size (width or radius) of a planet and the percentage of starlight it blocks (e.g., they would predict a planet 1/5 or 0.2 times the diameter of a star will block 1/5 of its light (20%)!). They also predict that if you double (or halve) a planet’s width it will double (or halve) the amount of light blocked.) But it is the planet’s projected area ($\pi r^2$) against the area of the star’s disk ($\pi R^2$) that matters. You may need to explicitly call out to students that for the purposes of a transit investigation, when thinking about the “size” of a planet, they should be thinking not just about its width, but rather its “radius-squared” – because that affects the area of light blockage.

Facilitate a class discussion of the two scenarios in Stage 4, which ask students to consider the fraction of the amount of starlight blocked by the “default” model planet, which is 0.2 times (or 1/5th) the radius of its star; and of a Jupiter-like planet, which would be 0.1 times, or 1/10 the radius of a sun-like star. If students naively predict the default model planet would block 1/5 of its star’s light, have them examine the diagrams on the page more closely:

1/5th radius = 1/25th area (.04)
(Star will dim from 100% to 96% brightness)

1/10th radius = 1/100th area (.01)
(Star will dim from 100% to 99% brightness)
In all cases, the amount of dimming ($\Delta B$) caused by a transiting planet of radius $r$ equals:

$$\Delta B = \frac{\pi r^2}{\pi R^2}$$

(and here we’re setting $R$, the Radius of the star, equal to 1)

You may wish to go over this math with students to help them become more facile with going back and forth between the size of a transiting planet and the fractional dimming of its star. Remember, when you and students create a light curve from your data, you will NOT know $r/R$. Instead, you will have a record of the percentage drop in the star’s light and will have to work backwards: if you were to measure a 3 percent drop from 100% to 97% of the star’s baseline brightness, what would such a planet’s size be? It would be the square root of 0.03, or .17 times its star’s radius!

What about an Earth-sized planet compared to a Sun-sized star? At 1/100th the radius of its star, an alien Earth would only block 1/10,000th, 0.0001 or 0.01% of its star’s light! This is why astronomers are using space-based telescopes, like NASA’s Kepler Mission, that can get above the distortions of our atmosphere to detect such tiny variations in the brightness of distant stars as earth-sized planets transit.

Stage 5 of the Modeling Lab encourages students to think more deeply about how the model predicts variations in the signal (the brightness graph or light curve), depending upon assumptions about 3 key features of any exoplanet they might observe: its size, its orbital speed, and its orbital tilt.

When students first click on Stage 5, the Graph is in the PREDICT Mode, where they can select a Big, Small, Fast, Slow, or Tilted planet, and then click and drag the graph to predict how this planet’s signal would differ from the Default, Medium size and speed, Edge-on planet.

By clicking on SIMULATE, the computer will actually calculate and graph an accurate representation of the fraction of the star’s area that is blocked by the visual model planet as it changes. Have students use the “ADJUST MODEL” panel to actively change the planets’ size, speed and tilt while they observe the resulting graph. Here, for example, they can actually test how doubling the planet’s size would quadruple the depth of the dip in brightness during the transit.

Assessment. The goal of Stage 5 is for students to save a final graph for a particular model planet, and to refine and save their verbal reasoning that explains in detail how at least 3 features of that graph are related to specific aspects of their model planet. The “MY SAVED MODEL” tab will save to their ExoLab account the last Graph and the last verbal Reasoning explanation that students enter in the Modeling Lab. If they log out of the ExoLab and return, the MY SAVED MODEL will still have their graph and explanation. You may wish to have students capture a screen shot of their Saved Model so that you can assess their understanding of what the model predicts.
**Stage 5 Simulation Mode** – Students can click on SIMULATE to see the graph respond accurately as they change the size, speed or tilt of the model exoplanet. Be sure students click “Save Graph” and “Save Work” to enter the final graph and explanation they want recorded in the “MY SAVED MODEL” tab.

---

**Stage 6 – Summary of the Model, and its strengths and limitations.**

This is a good time to facilitate a class discussion of the merits and weaknesses of the model being used for this project – by doing such an evaluation, students are participating in the
scientific practice of using models in the same way that professional planet hunters do (and as called for by the NGSS standards).

1. What is "the model" being used here?

In this project, the "model" refers to:
   a. Our visualization of an alien planet orbiting a star, edge-on or nearly edge-on, so it "transits" its star
   b. Our understanding of the physics of the transit; and
   c. The graphical representation of that understanding, in the form of a brightness curve.

The model embodies this understanding: The star's brightness is constant before and after the transit. The brightness dims at the start and end of the transit (on- and off-ramps). The brightness is lowest when the planet is entirely in front of the star. In this simple model, the brightness curve is completely symmetric.

2. What are the strengths of this model?

This simple model can be used to make predictions about the signal we would observe if we took a series of measurements of a star’s brightness over time, that had a transiting planet. For example, the model predicts:
   a. The quantitative relationship between the depth of a transit brightness graph and the relative size of the exoplanet compared to its star
   b. That there is a relationship between the orbital speed of an orbiting planet and the duration of the transit, and the period between consecutive transits. (For physics students, the model also can include the mathematical relationships of Kepler’s Laws to predict the distance of the planet from its star, although the computer model does not include this)
   c. The differences in the pattern, or shape, of a light curve resulting from a planet orbiting edge-on with respect to us here on Earth, vs. a tilted orbit that causes the planet’s disk to cross over just the top or bottom part of the star’s disk. (The model also predicts the case of NO transit if the orbit is tilted too far away from edge-on).

3. What are the model's limitations?

The simplified Modeling Lab visualization represents some things accurately, but other things it misrepresents, or omits, for example:
   a. A star is MUCH brighter that a planet (and is not transparent, like the star in this model!)
   b. In this visual model, the speed of the planet is not linked to its distance from the star (there is no gravitational physics engine to this computer model)
   c. The on- and off-ramps will not be straight lines, since the planet and star are disks.
   d. A star is not uniformly bright across its width – the edges of the disk are typically darker.
   e. The star may have "sunspots" that cause its brightness to vary (especially if the planet passes over one).
   f. The planet reflects a small amount of starlight before and after the transit (especially when it is just about to go behind the star).
g. Other planets nearby may affect the period of the planet's orbit, etc.

The model also does not take into account ANY effects on the ground, such as weather, moonlight, city lights, the atmosphere effect of rising or setting, etc. These are all things that will effect the observations and brightness measurements you and your students will make. You will learn how to account for them and try to minimize them in the Image Lab.

After the Modeling Lab, you will want to discuss how this model might inform the overall strategy for collecting telescope data for the investigation. How long is a transit? How many images will be needed? How closely spaced? Do you need to have images that are before or after the predicted transit as well as those that might be during the transit?
Activity 3 — TELESCOPE LAB

In this brief lab, students will use one of the MicroObservatory telescopes, built and maintained by the Harvard-Smithsonian Center for Astrophysics and located at the Whipple Observatory in Amado, Arizona to take a series of images of their "target" star. These images will form the basis of students' subsequent investigation.

SUGGESTIONS FOR LEADING THE LESSON.

Taking an image. Explain to students that they will control the robotic telescope remotely. They will select the target star and several observing times. At night, the telescope will automatically point to the star at the requested times and will take an image. The following morning, their images will be waiting for them in the Image Lab. The image will appear as pending until the telescope actually takes the photo during the night. NOTE: All times are Arizona time, where the telescopes are located.

Planning and managing student image requests. A calendar of which exoplanet systems are available as telescope targets each night is downloadable on the Teacher page. While students can take as many or as few of the available images of the target star as they wish, you may wish to assign them to particular time slots, e.g. Students 1-5 request the first half hour of slots; Students 6-10 request the next half hour of slots, etc. That way, during the Image Lab you can more easily and efficiently have different groups of students take responsibility for measuring subsets of the data. Since a typical 4-5 hour transit run will have 80 to 100 images, another way to allocate images among students is to have them take every 8th or 10th image (e.g., assign student 1 the first telescope time slot, and then every 8th slot after that; assign student 2 the second slot, and every 8th slot after that, etc). PLEASE NOTE: When YOU, the teacher, take just a single image using your class account, the ENTIRE set of images for the night will appear in your class image list in the Image Lab and be available to all students (just in case they forget to request an assigned observation 😊)

Exposure time. Explain that each exposure time is automatically set to 60 seconds. This uniformity allows all students, in all schools, to share and compare data. (If the exposure times were allowed to differ, this would affect the measured brightness of the target star.)

Opaque filter. Explain that the telescope will automatically take a so-called "dark image" — i.e., an image using an opaque filter that lets no light through. This image will be used to help calibrate students' measurements. As we'll see, these images will not be completely black, because the telescope itself produces some electronic noise. (In a dark room, you can see flashes and floaters produced not by any light but by the "noise" in your eyes, retinas and brain.) This dark image will be waiting for each student with his or her other images.
ABOUT THE PLANETARIUM. The interactive planetarium shows a map of the sky as it looks right now at the Arizona telescope site. You can change the time to see how the sky would look at any other time. And you can scan the sky in any direction. (Use the arrow keys or click on the map and use the mouse.)

When you select a target star, the planetarium moves to the predicted location of the star for the beginning of the night’s observing run. The planetarium is also useful for seeing whether the Moon might interfere with your measurements.
**The target Exoplanet systems.** Currently there are more than two dozen stars with recently discovered exoplanets orbiting them in the MicroObservatory target list. As scientists discover more of these systems that are observable from our telescopes in Arizona, the list will grow. While your students will be observing stars where orbiting planets have previously been discovered, each set of telescope data they collect will consist of brand new observations of that system *that have never been analyzed by anyone before*. The ExoLab curriculum focuses on engaging your students in the authentic data analysis procedures that the original discoverers used to determine the features of the observed exoplanet from the transit light curve. But the details of the transits that your students may (or may not) observe and analyze are NOT foregone conclusions. Depending upon the quality of the telescope data and the precision of your students’ analysis, the light curves that they generate can yield discoveries on a number of fronts—from unexpected variation in the host or comparison stars, to detections of abnormalities in our telescope’s CCD detector. The observations of many transits by many ExoLab classrooms over time even have the potential to contribute to discoveries of additional planets orbiting these stars!

**BACKGROUND INFO.** The MicroObservatory telescope, a reflecting telescope with a 6-inch mirror, is tiny compared to the world’s largest telescopes, but it can see a billion light-years into space. This telescope magnifies only about 30 times, but its 6 inch “pupil” and CCD detector gathers about 500,000 times more light than your own eye can.

**Demo images.** Students may find images of stars to be visually boring (it's just a field a white dots). To enliven the class, and to give a feeling for the immensity of the universe, a sample of galaxy images are also available in the Demo Images list within Image Lab. Explain that the galaxies are huge collections of stars far beyond our own Milky Way galaxy. (We can't make out individual stars in these distant galaxies. All the stars we see with the telescope are within our own Milky Way galaxy.) Students can learn more about the MicroObservatory telescopes, and even use them to take their own images of non-exoplanet targets, at www.microobservatory.org.
Activity 4 — IMAGE LAB

PURPOSE. In this lab, students will attempt to detect an alien world, by looking for a dimming of the star’s light as the planet passes in front. To analyze their images in Part 1, students will:

- **Inspect the images** that they took with the telescope, working only with images unmarred by clouds.
- **Identify their target star** and two comparison stars, using a star chart provided.
- **Measure the brightness of their star** in each image, along with the brightness of two comparison stars.
- **Plot the (relative) brightness of their star**, compared to the comparison stars, for each image.
- **Inspect the resulting graph** (“light-curve”), to see if they detect a dip in the star’s brightness that might indicate a transiting planet.

In Part 2 of this lab, students will look at their **brightness graph** to become “data detectives,” to see if they can use the tools provided to:

- **Identify areas of concern** in their data—that is, “messy” parts of their graph that might call for explanation.
- **Identify the factors** that might account for the messiness in their graph (such as clouds, altitude above the horizon, moonlight, etc.)

NGSS EDUCATIONAL OBJECTIVES. This lab provides superb opportunities to highlight specific practices that are important throughout the sciences in **carrying out investigations** and in **analyzing data**. As a result of this lab, students should be able to:

- Explain the importance of **calibrating (“zeroing”) their instrument**. (*Students do this by subtracting a “dark” image*)
- Explain the use of a **control group** or **internal control**. (*Students compare their target star brightness to comparison stars; and they insure they are only measuring the brightness of the star by subtracting out the night sky*)
- Identify **significant features** (*i.e. the transit*) in their authentic data.
- Identify **unexpected or discordant features** in their data, and explain the confounding environmental factors and sources of error that might account for these features.
SUGGESTIONS FOR LEADING THE LESSON.

IMAGE LAB PART 1: ANALYZE IMAGES

Image Lab Overview (Page 1). The Image Lab is the most time- and labor-intensive part of the ExoLab—you should expect to spend at least 2 class periods on this part of the lab (and potentially more, especially if your class is looking at more than a single target star). Collectively, the students in your class will need to make brightness measurements on the 70-100 digital images that the telescope takes of a single target on a single night.

When you first click on the Image Lab, the “Analyze Images” Tool is highlighted. The 9 numbered pages of this tool walk students through the steps of examining and making measurements on a SINGLE image. Most teachers have found it works best to facilitate a class discussion as students go through these steps, pointing out the parts of the procedure that are aimed at minimizing sources of error.

Inspect Your Telescope Images (Page 2)

Have students look at one of their images. (On the ANALYZE IMAGES menu, press Show List, then select an image.) Expand their imaginations: These dots are stars, many of them orbited by planets — alien worlds that may or may not have life on them.

Explain what is amazing about this Lab: You will be able to detect a planet and tell something about it, just from measuring the starlight.

Laboratory for the Study of Exoplanets  https://www.cfa.harvard.edu/smgphp/otherworlds/ExoLab/  Activity 4 Image Lab –p2
Remind students that a planet is much smaller than its star, so they are looking for a tiny dip in the star’s light — a few percent at most. Detecting the planet requires precision measurements, so students will need to work carefully.

How a Digital Image Works (Page 3). Have students move the mouse cursor over their image. The readout at the bottom of the image shows the brightness of each pixel. The brightness comes in 4096 grey levels, ranging from 0 (black pixel) to 4095 (white pixel).
The brightness number is directly proportional to the amount of light that fell on the telescope’s light-sensing chip. (E.g. a pixel with brightness 1500 received three times as much light as a pixel with brightness of 500.) The brightness numbers have no units: That’s fine, because we are only interested in comparing brightnesses among objects and over time—not in determining the absolute amount of light the telescope received.

Examine the brightness number below the magnifying window. It measures the total brightness of all the pixels inside the yellow circle. By positioning a star within the circle, we can get a standard measurement—the brightness within a circle whose size is the same for all students and all classrooms. This lets us combine our data across observers.

**Calibrating The Telescope (Page 4).** Explain to students how they will correct for certain errors. Explain that the target star is not the only thing that will contribute to our light measurement. Like every measuring instrument, the telescope’s light-sensing chip itself adds "noise" to the measurement. We’ll have to subtract this noise from our measurement. How do we know how much the telescope itself contributes? Simple: We take an image with an opaque filter that lets no light through ("Dark Image"). The resulting image represents the contribution from the telescope’s light sensor.

To see this, have students open the Dark Image from the same night as the target (the Dark is typically at the bottom of the list target images) and run their cursor over it. Note that the brightness of every pixel is not zero. Evidently, the light-sensor adds its own contribution to our measurement of brightness. To subtract this instrument noise out, students should press Subtract Dark. The dark image will now automatically be subtracted from every image during your session. You do not have to worry about it again—unless you refresh the page or go to another page. (An alert will warn you if you try to Calculate and Record a measurement without having loaded a Dark Image and pressed Subtract Dark at the start of your session.)

Explain to students that the Dark Subtract is a way of "zeroing" or calibrating their instrument—something done with all scientific instruments, such as pH meters, electronic scales and balances, spectrometers, etc.

**Uh Oh--Another Problem – Background Sky Light (Page 5).** First, have everyone open the first class image of your star. Students may notice the typical level of brightness of the pixels is now lower (than Page 3) since the dark image is now subtracted. But the dark sky between the stars is NOT zero! Explain there is another error besides the instrument signal that can make the star brightness measurement appear too high: the sky between the stars in not completely black, due to things ranging from twilight light, to moon light, to city lights, to haze. This means that when you measure your star’s brightness, in reality you’ll be measuring the brightness of the star PLUS this background sky light. To correct for this, students will make two measurements of this background sky brightness, and then subtract the average of these from the target star measurement.
Using an Internal Control (Page 6). This page explains why students will also measure two comparison stars in addition to the target star. A dip in the target star’s brightness could simply be due to a passing cloud during the observations, or a dimming due to the starlight passing through more and more of Earth’s atmosphere as it sets. How can you distinguish between the ho-hum possibility that you are just detecting a cloud and the amazing possibility that you are actual planet orbiting that star? By plotting the ratio of our star’s brightness to the brightness of 2 comparison stars in the same field of view, you will eliminate the effect of clouds, haze, airmass, etc. (The ExoLab team at the Harvard-Smithsonian Center for Astrophysics has specially selected the comparison stars to insure that they themselves are not variable stars – another effect that can make it more difficult to pick out an exoplanet’s signal from the noise).

Finding Your Star and Measuring Brightness (Pages 7 and 8).
You may wish to direct students to the YouTube Tutorial for Measuring Brightness: http://youtu.be/qMU389InCYQ (Linked from the Teacher Page). Appendix A of this Image Lab Teacher Guide also has a step-by-step pictorial guide for measuring brightness.

One of the most difficult parts of this investigation is identifying the target star—measuring the wrong target or comparison star is the most frequent source of human error introduced into the ExoLab. Pages 7 and 8 describe how to locate your target and comparison stars using a transparent Finder Chart, and then how to measure their brightness using the cursor and yellow circles.
Calculate Brightness (Page 9). So that students fully understand the math behind the measurements they are making, Page 9 guides students in doing the calculations by hand for at least one image. This is the calculation for “Relative Brightness” being done by the computer for each image when they click the “Calculate & Record” button.

Teaching Tips:

Before students start taking measurements on multiple images, have them check to make sure they are using images of good quality. Smearred or unclear images can give bad measurements and make it hard to see a dip in the transit graph. If there are doubts about an image, have students decide whether to skip that image or not by using the “What’s Wrong With My Image?” in Appendix B to this Image Lab Teacher guide. As students are making their brightness measurements, you may want to project the emerging light curve to the whole class using the “Graph Brightness” tool. This way, you can quickly identify any students who may be measuring the wrong star and thereby creating outliers, before they measure too many images!

**IMAGE LAB PART 2 – GRAPH BRIGHTNESS**

Be sure not to skip the 6 pages of this activity! Analyzing data quality is one of the most important aspects of an authentic research investigation, and whether your students got a completely messy and chaotic brightness graph for their target star, or a “textbook” transit light curve (unlikely!), there is much to learn from a close inspection of their reduced data.

Displaying Your Data (Page 1). When students first click on “Graph Brightness,” they will only see a graph of the data points they personally created through image measurements in green, and these likely do not tell the whole story. By clicking on “Class Graph,” they will be able to see the measurements of the rest of the class in red, added to their own data.
Why Are My Data So Messy? (Page 2). Students may be surprised that their graph does not look at all like the Model light curve they created in the Modeling Lab. But this kind of scattered data is typical of real world research. At the end of the lab, you may wish to have students look up discovery papers of the exoplanet targets they are observing, to see that the discovery light curves of transiting planets often look very similar to their own.

Real Data: 3 examples of ExoLab class light curves show good quality data (HATP36); scattered data with gaps due to cloudy images (Qatar2); and scattered data with many students measuring wrong stars (WASP43)
A Closer Look At Your Data (Pages 3 and 4). The ExoLab graphing software provides a tool for students to examine the individual Components (Target star, Comparison stars, Background sky) of each relative brightness measurement. A second tool allows them to see the Altitude of the target star in the sky at each observation the telescope made during the night. These can be extremely useful in assessing the quality of your data.

A Field Guide to Messy Data (Page 5). This interactive tutorial walks students through six different real-world factors that can affect the quality of their data. For each factor, have students click on the blue arrow to see light curves, component graphs, and altitude data that demonstrate the effect that factor could have on their own data.
You may wish to facilitate a class discussion of the factors that commonly interfere with students’ brightness measurements:

- **Altitude of the star.** (Near the horizon, stars appear dimmer and the background sky brighter.)
- **Clouds and haze.** (Thin clouds and haze, *even when not easily seen in the telescope image*, brighten the night sky and increase scatter.)
- **Moon.** (When the moon rises, the night sky becomes brighter, often contributing to much greater scatter in the data because the signal to noise ratio goes way down.)
- **Wrong star.** (This is a common source of human error, identifiable in the component graph by outlier dots that do not align with the rest of the data set.)
- **Atmosphere.** (Even the highest quality image data captured on a moonless clear night from a target high in the sky will have natural variation and scatter. The Earth’s turbulent atmosphere makes the stars twinkle. This is one reason NASA’s Kepler space-based telescope can make much more precise measurements.)
- **Star color.** (Just as our sun reddens as it sets, the same happens to the stars students are measuring. But if the component stars are bluer or redder than the target star, the atmosphere will affect them differently.)

Here are two other factors that are not covered in the tutorial; you or your students may come up with others as well:

- **Intrinsic star brightness.** (The dimmer the star, the lower the signal / noise ratio, and the higher the scatter – see, for example, the graphs of HATP36 and Qatar2 on pages 7 and 8 of this guide.)
- **Time of night.** (As dawn approaches, the background sky brightens, so telescope images that are taken in the early morning hours just before sunrise typically produce more scattered data, as do images taken just after sunset.)

**Assessment—Data Detective (Page 6).** This page of the Image Lab allows students to pull all their new-found understanding of messy data together by recording their specific impressions about their class data and the factors that may have affected it. Specifically, they are asked to

1) comment on the difference between their graph of real data, and the one they predicted in Modeling Lab; 2) identify specific points or regions of the graph that are problematic, given the prediction of the Modeling Lab; and 3) make specific claims about the factors that affected their graph providing evidence from the Components or Altitude tools. Remind them to click “Save Work so their comments are saved to their account. You may wish to have students capture screen shots of this page – including their Brightness, Components, and Altitude graphs to hand in, or to prepare a final report at the end of the ExoLab.
<table>
<thead>
<tr>
<th>Step 1:</th>
<th><img src="image" alt="Image Lab Appendix A" /></th>
</tr>
</thead>
<tbody>
<tr>
<td>Click “show my list” to get a list of your available images.</td>
<td></td>
</tr>
<tr>
<td>You can either select from “My Images” or “Class Images.”</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 2:</th>
<th><img src="image" alt="Image Lab Appendix A" /></th>
</tr>
</thead>
<tbody>
<tr>
<td>Select the dark image for the set you’d like to measure. The file, starting with Dark-C, will come directly after the image set you’d like to measure.</td>
<td></td>
</tr>
<tr>
<td>It will have a similar filename as your images, signifying it was taken on the same date.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 3:</th>
<th><img src="image" alt="Image Lab Appendix A" /></th>
</tr>
</thead>
<tbody>
<tr>
<td>Select “Subtract dark” to remove excess noise from your images.</td>
<td></td>
</tr>
</tbody>
</table>
Step 4:

Click “show my list” to bring up the images you can measure.

Scroll up from your dark image to select the first image in your set to measure.

---

Step 5:

Click “Locate Target Star” to bring up the target-star overlay.

The T indicates your target star, and the two Cs show the two comparison stars.

Drag the comparison chart over your measurement image, and line up the star patterns carefully until they match.
Step 6:
Measure your target star by clicking on it, making sure to get the entire star within the measurement circle. Use the magnified view in the upper right hand corner to help.

Step 7:
Measure two comparison stars by first clicking on a comparison star box, then clicking the star.

Be sure to click each box before making your measurement. If you click twice in a row, you'll overwrite the previous data.
Step 8:
Measure two dark parts of the sky. Make sure there are no stars in your dark sky field. Use the magnified view on the upper right to help.

Click on each dark sky measurement box before making the measurement.

Step 9:
Click the “Calculate & Record” button to calculate the relative brightness of your target star using your measurements, and record the result. This will happen automatically.

Step 10:
You can advance to the next image and go back to the previous image, by clicking on these arrows.

You can also select images from the “Show my list” menu.
Some background information:

When you click the “calculate and record” button, a few things happen behind the scenes before the program can arrive at the “relative brightness” measurement. Here’s how the brightness is calculated!

1. The background sky in your images isn’t completely dark, and have pixel values of well above 0. In order to get a more accurate reading of just how bright your stars are, we need to know what our baseline for “dark” really is. So, find the average of your two background sky measurements.

2. Subtract the average background sky measurement from your three star measurements - the target star, and two comparison stars.

3. Next, we’ll need a good baseline for the brightness of your comparison stars, so we can compare the value to the brightness of the target star. Find the average brightness of the two dark-subtracted comparison stars to find one value.

4. Finally, divide your brightness for the background-subtracted comparison star by the average of the two background-subtracted comparison stars, and you have your relative brightness!
### My image is hazy and white, but I can still see a few stars. Also there are a bunch of donut-shaped things in my image!

**Source of error:** There were some clouds in the sky that floated over your field of view. The donut-shaped rings are caused by tiny specks of dust on the detector. They're always there, but are much easier to see when it's cloudy.

**What to do:** Since you can still see the stars in this image, try taking a measurement. If it was too cloudy to see your stars, skip the image.

---

### My image is all black or all white! I can’t see a thing!

**Source of error:** An image that is all one color has most likely been overexposed - meaning that the sky was brighter than anticipated. This usually happens when the sky is very cloudy, as clouds are very bright.

**What to do:** Since it was too cloudy for you to see any stars in your image, skip measuring this one and move on to any non-cloudy images in your set.

---

### There’s a bright streak running through my image!

**Source of error:** You’ve found a satellite passing through your field of view during exposure! Sometimes satellites, meteors, asteroids, planes and even birds pass through a field of view during an exposure.

**What to do:** If the streak passes through any of your stars, you’ll have to skip the image. If however, the streak misses your target star and two comparison stars, make your measurements as usual.
All I see are tiny white dots, but they don’t look like stars.

Source of error: The small white dots are actually “hot pixels,” or electronic noise that’s showing up on your image. They are always there, but are much less noticeable when there are stars. If you only see the electronic noise, the image was overexposed (most likely because of a cloudy night).

What to do: Since you can’t see any stars, you can’t measure this image, and should skip it.

My stars aren’t round, but are more oval-shaped.

Source of error: The telescope wasn’t tracking the sky properly, and so didn’t adjust perfectly along with the rotating Earth.

What to do: If you can still fit the whole star inside your measurement circles, you can still use the image. If it’s too large to fit inside and cuts off some of the brightness, skip measuring that image.
NOTE: This DataLab Activity Guide will be updated soon to reflect April 2015 changes

DATA LAB

PURPOSE. In this lab, students analyze and interpret quantitative features of their brightness graph to determine the size of the planet and the nature of its orbit. In doing so, students apply statistical & mathematical skills as well as their understanding of light, gravity, and the model from the Modeling Lab. Students will:

- Inspect the graph (sometimes called a “light curve”) that they generated in the Image Lab, and consider how confidently they can conclude that they’ve detected a transiting planet, given noisy data.
- Compare and contrast their data with additional data for the same star and consider whether this data makes them more or less confident.
- Use a Transit Modeling Tool that allows students to test different transit models (deep or shallow; long or short duration; long or short ingress and egress) against their real-world data.
- Use statistical analysis tools to find the best fit of the Model Transit Graph to their data. Students will determine the simplified model that is best supported by the data they collected, including quantitative estimates for their baseline and transit dip brightness values, and a measurement of the uncertainty of those values.

For the culmination of this Lab students will:

- Interpret the light curve and its quantitative parameters to determine important features of the planet: its size, orbital tilt, and distance from its star.
  - They’ll derive the planet’s size relative to its star from the fractional dip in the star’s brightness.
  - They’ll use the shape of their light curve data to draw conclusions about the orientation of the planet’s orbit with respect to Earth’s viewpoint (edge-on or tilted).
  - They’ll estimate the relative distance of the planet from its star based on the duration of their measured transit.
  - They will summarize what they’ve learned by submitting a Press Conference Briefing to their Journal.

EDUCATIONAL OBJECTIVES. Like the Image Lab, this Data Lab also highlights specific science practices that are important throughout the sciences. In particular, this Lab gives students practice in interpreting data in light of a model that explains and makes predictions for what
the data should look like. Students must **deal with uncertainty** as they **interpret and draw conclusions from their data**. As a result of this lab, students should be able to:

- Explain how all **measurements have inherent uncertainty**, and that every **measuring instrument contributes noise** (so there will always be scatter in the data when you look closely enough).
- Describe how **obtaining more data helps to distinguish a signal from the noise**.
- Describe how using **statistical measures** and a **simplified model** can help us draw conclusions when there is scatter in the data. (We can choose a model that minimizes the variance between the data and the model; and we can assess the amount of scatter in the data, e.g. *standard deviation or standard error*).

**SUGGESTIONS FOR LEADING THE LESSON.**

**Introduce the Lab.** As students open the Data Lab, the graph will display the communal class light curve of the star they measured in the Image Lab. (If the class investigated more than one star, you can use the “Other Stars” link to choose from a list of stars for which you have light curves.)

Depending upon some of the factors you discussed in the Image Lab, your class may have a very messy light curve with a lot of scatter, or a curve with a more definitive dip amidst the scatter. Explain that **finding a signal in the noise of random variation is fundamental to scientific investigations**: (“Is the Earth getting warmer? Does aspirin help prevent heart attacks? Is Serena Williams’ tennis game at its peak?”). The signal we are looking for in this investigation is a particular pattern of changing brightness—the tell-tale transit dip that students predicted in the Modeling Lab. But detecting exoplanets is very challenging, with many sources of noise and random scatter—the telescope instrument contributes noise; the Earth’s atmosphere (even on the clearest of nights) distorts the light from the stars. (We can see this with our naked eye as twinkling!)

**Detection Challenge 1 and 1b: Do you have evidence for a planet?**

1. Following the directions on the Data Lab sidebar, students will begin by examining their graph, and deciding if they have evidence for a transit. You may want to highlight this key idea: *Don’t look for answers. Look for results that you can justify with the evidence you have gathered.* (In real science investigations like this one, Nature doesn’t come with an answer key!) Encourage students to describe the aspects of their data that give them confidence (or not) in their results. Do they see the tell-tale pattern of a transit dip in their data?

1b. After putting their first impressions in the Challenge 1 text box, students should click “Save and Continue”. At this point, they can click on “Show Others’ Data” to see additional data point from another class’ measurements of the same star on a different night. They can also click and drag their cursor on the graph to highlight a region they think might where the dip occurs.

[NOTE: The “Show Astronomers’ Prediction” Button will not work until Challenge 3 of the Data Lab.]

Activity 5 Data Lab — Page 2
Tell students to be sure to click “Save and Continue” to save their additional thoughts about whether this additional evidence gives them any more confidence they have detected an exoplanet.

Data Lab Challenge 1b.
Detection Challenge 2: How do I fit a transit model to the data?

This part of the data lab immerses students in one of the central practices of authentic science—using models to analyze and interpret real-world data. Explain to students that the straight-lined graph superimposed over their data is a Transit Modeling Tool. The straight line segments represent our understanding of the physics of the real world phenomena: a baseline stellar brightness; a maximum dip level; and “on and off ramps” where the planet is moving in front of the edge of the star’s disk. Their job is to move the Red, Yellow, and Green circles to where they think these segments align with (or fit) their data.

The Challenge 2 text box asks students why they think their data don’t exactly match the pattern predicted by the model. They should answer this and click “Save and Continue” to be sure to save the Challenge 2 baseline and dip level brightness values into their journal. AFTER they have answered this, you may want to take time to explicitly discuss the use of models in science – see the discussion in the appendix at the end of this Data Lab guide.
Detection Challenge 3: Which transit model best fits my data?

This part of the Lab gives students additional analytical tools to i) optimize the fit between their data and the Transit Model, ii) refine their quantitative values for the depth and duration of the transit they observed, and iii) reflect upon the uncertainty inherent in their measurements.

Now, as students move the Red, Yellow, and Green circles, they will see thin grey lines that represent the distance between their individual measurements and the Transit Model. A banner at the bottom of the graph illustrates “Current” and “Best Score” values that dynamically change as students manipulate the model, allowing them to actively test which specific model minimizes the summed distance of all the point from the straight-line graph.

Uncertainty: The bottom banner also shows a dynamically changing value representing the “standard error” – a statistical calculation that depends both on the number of points in the data set AND the scatter around the particular transit model being tested. For a clear transit
data set which has truly random variation, this bar represents the “95% confidence interval” – that is, if you took an infinite number of measurements of this quantity, the probability is 95% that the average would fall somewhere within this interval. ... But of course, there may be many other non-random (systematic) variations that can affect the fit of your class data to a particular transit model (human error, clouds, moon, etc), and that will also affect the uncertainty. You may want to have your students reflect on the fact that even though there may be significant uncertainty in their baseline and dip level values, they are still able to detect the “signal” of the planet crossing in front of its star. Be sure to have them click “Save and Continue” before moving on to Challenge 4.

**Detection Challenge 4: How big is my planet?**

For many students (and teachers), these final steps are the most exciting ones, because this is where their measurements of a dot of light turn into results that describe the physical characteristics of a real world orbiting another star!

**Size:** To determine the size of the planet, remember the simple geometry of the model of a transit. Because the (projected) shapes of both the star and the planet are very nearly circular disks, the percentage dip in brightness caused by the black disk of the planet is simply the ratio of the area of the planet to the area of the star:

\[
\Delta B = 100\% \left( \frac{\pi r^2}{\pi R^2} \right)
\]

(e.g., a total 100% dip in brightness would mean the planet was the same radius as the star)

This means that you can easily calculate the planet/star size ratio \(r/R\) by taking the square root of the fraction of starlight blocked by your exoplanet:

\[
\frac{r}{R} = \sqrt{\frac{\Delta B}{100\%}}
\]

For the example of HATP 19 illustrated in Challenge 3, above, the fractional dip in brightness (\(\Delta B/100\%\)) would be:

**BASELINE – DIP LEVEL** | 1.200 – 1.174 = 0.026 | **= 0.022**
---|---|---
**BASELINE LEVEL** | 1.200 | 1.200

**The square root of 0.022 = 0.148**, meaning that HATP 19, according to this dataset, is 0.148 times the diameter of its star. That’s larger than the size of the giant planet Jupiter, compared to the Sun. By contrast, the Earth is only 0.01 times the diameter of the Sun, so it would block out only 0.0001 of the Sun’s light (i.e. 0.01%) during a transit. To detect an Earth-sized planet would require 100 times more precision than the MicroObservatory telescope.
To enter the correct value in the SIZE textbox, students should use their values for “baseline” and “dip” brightness and follow these 4 steps:

1. BASELINE BRIGHTNESS LEVEL FROM CHALLENGE 3  
2. DIP LEVEL BRIGHTNESS LEVEL FROM CHALLENGE 3 
3. PERCENTAGE DIP, $\Delta B/100\% = (1. - 2.)/1.$: 
4. SIZE RATIO OF PLANET/STAR, $r/R = \sqrt{3.}$: 

Enter the result from Step 4 into the textbox in Challenge 4, and click “Save and Continue” to save this value into the Journal.

**Detection Challenge 5: Is the planet’s orbit tilted?**

In order to even see a transit, the orbit must be fairly “Edge-On” with respect to our view from Earth. Transits for most of the stars have a flat “trough”, indicating that the planet’s orbit is nearly 90 degrees edge-on, and the planet transits across the middle of the main face of the star. But for the star TrES3, for example, the planet’s orbit is tilted 8% from an edge-on view (it has an “inclination” of 82 degrees), so the transiting disk of the planet just grazes the star. The transit graph looks more like a “V”: As soon as there is a dip, the brightness returns to the baseline level. The precision of students’ data should typically allow them to identify whether their observations indicate a more edge-on, or more tilted, orbital plane. Have students click on the graph image that represents their choice, and then click “Save and Continue”.

**Detection Challenge 6: How close is the planet to its star?**

For this final important planetary characteristic, you’ll use Kepler’s 3rd Law, the mathematical relationship that describes how the closer a planet is to its star, the faster it moves—and so the shorter its transit time.

Typically, Kepler’s law is expressed as a relationship between the period (T) of the planet (it’s year, or Time for one orbit), and the “semi-major axis” of its elliptical orbit, which for a circular orbit, is simply R, the distance between the star and planet. Kepler discovered that $R^3 = T^2$, where R is expressed in Astronomical Units (AU, the average Earth-Sun distance), and T in units of “Earth” years.

In this calculation, you and your students will assume a circular orbit, and also assume that the target star is Sun-like (the same mass and diameter), so that you can directly compare the orbital speed and distance of your exoplanet with that of the Earth. (Of course your result will then only be approximate if the target star is not the same mass or diameter of the Sun.)
Using Transit Duration and Orbital Speed to Determine Planetary Distance $R$

While your class typically will not know the period (T) of their planet (they would have to observe at least 2 transits in a row to determine this), they DO have the transit duration, which, as a measure of the planet’s orbital speed, is proportional to the square root of its orbital distance from its star (longer duration transits mean larger orbital distances).

Challenge 6 Textbox: Your students can “read off” the orbital distance of their planet from the graphical chart on the page. For more math-based courses, you might choose to have students calculate their planet’s orbital speed and then substitute that into Kepler’s Law to calculate the orbital distance. If the exoplanet transits the star in, say, 3 hours, then its approximate speed (v) is simply the diameter of a Sun-like star (1.4 million km) divided by the transit duration (3 hrs) = 467,000 km/hr. By comparing this orbital speed with the Earth’s orbital speed (about 100,000 km/hr)

Here’s how to use orbital speed, $v$, in Kepler’s equation rather than the period, T:

It should be straightforward to see that the period (T) times the orbital speed (v) equals the orbital circumference $2\pi R$, so that $T = 2\pi R/v$. Substituting this in to Kepler’s equation $R^3 = T^2$, we have:

$$R^3 = 4\pi^2 R^2 \frac{v^2}{v^2}$$

Now, you can see that the distance $R$ is proportional to $1/v^2$

So... if your exoplanet’s orbital speed is 4.7 times that of the Earth (as above), then its distance from its star is $1/(4.7)^2$ or 0.045 AU!

The importance of this distance is that it bears on whether the planet might be habitable. The planets detected in this project are all very close to their stars. Liquid water would not exist on these planets, and neither would life.

Detection Challenge 7: Publish your results and prepare a press conference briefing!!

Don’t forget to reflect on what is amazing about this Lab: Your class was able to detect a planet and tell something about it, just from measuring the starlight! This last page of the DataLab provides an opportunity for students to reflect upon and sum up their finding through the whole investigation. They can open up their journal to refresh their memory about all the steps they went through as the prepare the text for this last step of the Data Lab.
NOTE: This Community activity guide will be updated soon to reflect April 2015 changes

COMMUNITY

PURPOSE. This page on the ExoLab website archives the light curve data of classrooms that have published their work to the site, and allows students to see the work of other schools participating in the project. This record of authentic data encourages students to:

- **Inspect and compare** the results of their own class with those of other classrooms nationwide.

- **Compare the light curve for their target star** with other light curves from the same target star, and with light curves from other transiting planetary systems.

EDUCATIONAL OBJECTIVES. This communal archive provides an opportunity to reflect on the collaborative nature of science. After examining this Community data page, students should be able to:

- **Identify additional information** gained by looking at the results of other observing groups.

- **Identify additional questions** raised by the results of other observing groups.

PUBLISHING CLASSROOM DATA.

Only teachers can publish their classroom data to the ExoLab site. This is done within the Teacher’s Journal, on the Data Lab II page:

Teachers will see a “Publish Results” button at the top of that page, next to a pull-down list of target stars for which the class has collected data.

To be sure that you have a data set that you and your class think is ready for
publishing to the world at large, be sure to examine your class data for the target star(s) you measured using the pull down list within the Data Lab section of the ExoLab site:

Within a short time after you have published your class data, you can look for it on the Community page, searching by either classroom, or star system:

Note that as you scroll over the school names, the data set contributed by that school will be highlighted in the cumulative light curve for that transiting planetary system.