The Truth Is Out There: Finding Exoplanets

Klint Kanopka
Academy at Palumbo

Overview

One of the hottest topics in physics today is the search for potentially habitable planets outside of our own solar system. These planets, known as exoplanets, stimulate the imagination in a way that any student can relate to, regardless of the amount of physics knowledge they possess. The search for these planets seems incredibly difficult, however the principles scientists use to find them are based in the content covered in a relatively standard introductory physics course.

This unit attempts to compile these techniques and frame them in a way that is accessible to a typical high school student taking an introductory course in mechanics, even if they can't access the Spitzer Space Telescope. Besides serving as an interesting hook to force students to access prior knowledge regarding waves and motion, it serves the larger goal of making students acutely aware of the fact that the physics they learn in school is not different than the physics used by research scientists. Those scientists are just more specialized and have fancier equipment. Since the data used to find these exoplanets is widely available, it might even inspire students to begin their research careers early!

Rationale

The traditional Biology-Chemistry-Physics sequence in high school does a terrible job of representing the day-to-day life of a research scientist. The first major problem is that the information is incredibly segregated. Every year, students feel like they get a "reset" and all of the science content they've learned previously is out the window to make room for something new. Since physics is typically the last course a student takes at the high school level, this effect is even more pronounced, because insights gained in physics could be used to better understand phenomena in biology and chemistry. This unit attempts to take the current hot topic of searching for exoplanets and life beyond our solar system and connect it to the classical physics that my students already know, while also allowing some of the biology and chemistry they've learned in past years to inform their work.

Demographics

This unit is designed for 11th grade students currently enrolled in a general physics course meeting five days per week for 48 minutes at a time. The Academy at Palumbo is an academic magnet school in the School District of Philadelphia. Students come from all over the city to attend and our racial demographics are quite close to the demographics of the city as a whole. Despite being an academic school, students typically arrive to physics with gaps in their previous math education. Most students will be taking Algebra 2 concurrently with physics, though a small minority will be enrolled in Geometry or Precalculus, depending on individual level. As such, the unit is not concerned with using mathematics beyond manipulating literal equations and some basic trigonometry that students should have already used in physics. Students at our school have already taken biology and chemistry, so when it comes time to consider searching for life beyond our solar system, a small amount of their prior knowledge from those courses will be drawn upon.

Background Information

This unit belongs in an introductory physics course, though the topics that students need to have covered in advance are relatively limited. From a mechanics perspective, students should have a firm grasp of Newton's Laws and Newtonian Gravity. Since gravity is the force that drives all of the motion we will be looking for in this unit, students should be comfortable with it. Additionally, students will need experience with and a good understanding of circular motion. Even though orbital motion is elliptical, the circular approximation gives the same results as using Kepler's Laws. Students don't expressly need to know Kepler's Laws, making this unit appropriate for an AP Physics 1 course. Finally, students will need to know about the conservation of linear momentum and center of mass.

For a course like AP Physics 1 or a general mechanics course, there may not be much student exposure to light and electromagnetic waves. During a waves chapter, students will get the necessary exposure to the Doppler effect, but the EM spectrum and the color of light will need to be added to the course for some of the detection techniques and the general idea of observing with a telescope to make complete sense.

Detection Techniques

This unit is primarily concerned with the understanding and implementation of five types of planet detection techniques and reinforcing the notion for students that the discoveries they hear about in the news are rooted in the physics they are learning in class. Using the principles discussed above, students can easily grasp four of the five methods. The fifth, gravitational microlensing, requires students to accept Einstein's description of gravity.

To understand these methods, their uses and their limitations, students need to understand that all of them are dependent upon gathering light from something exceedingly far away. In my experience, when students hear about new discoveries, they frequently infer that there must be corresponding new science. With extrasolar planets, this isn't really the case. The reality is that by deploying better and better telescopes, we have become much better at gathering small amounts of light from systems that are extremely far away. As telescopes improve, students should expect these sorts of discoveries to become more and more commonplace. With the idea that all of these detections depend on gathering light, I've organized the five detection methods into what I believe is the most logical order of presentation.

Direct Imaging

Direct imaging is the technique of taking a picture of a planet as it orbits a star. To students, the idea of confirming something's existence by photographing it should seem extremely logical. In practice, direct imaging seems like it should be the simplest solution, but in reality, it's nearly (though not completely) impossible. The challenge is best summed up this way: Stars are enormous and emit light. Planets are tiny and do not emit light. Any light we collect "from" a planet is really just reflected from a nearby star and into our telescope. To complicate matters further, remember that these systems are extremely far away. As a model, imagine being in Philadelphia and looking at a glowing grapefruit in San Francisco. Then, in the neighborhood of that glowing grapefruit is a tiny sphere the size of the tip of a ballpoint pen. Now, think about how easy it is to take a great picture of a person when the sun is in the background. Put this all together and the issues with taking pictures of planets directly become glaringly obvious.

All of the issues aside, sometimes scientists can actually image planets directly. In certain rare situations, scientists can use a coronagraph to block out the emitted directly from the star in order to more easily see the objects orbiting in its neighborhood. As of the writing of this unit, scientists have directly imaged 22 of the approximately 2,000 exoplanets that have been discovered, making the technique good for only about 1% of the discoveries made so far.

Transit

The transit method works on the same principle as the sun visors in an automobile. In your car, you pull the visor down to put an object in front of the sun that blocks some of the light. When you have multiple pictures of the same star over a long period of time, you can plot the observed brightness of the star. If the brightness goes down, you can make the assumption that there is some object in between you and the star blocking some of the light. If this dimming of the star occurs at regular intervals, you can make the assumption that the thing in between you and the star is a planet that is orbiting the star. Astronomers describe this as a "transit."

By making measurements of how often this dimming occurs, physicists can determine the orbital period of the planet. By looking at how much of the light is blocked out, they can determine the size of the planet, as well. Being able to determine the size of the planet actually makes transit measurements key to determining the density of a planet, and categorizing is as made of gas (gaseous) or made of rocks (terrestrial). To determine the size of the planet, you can relate the area of the planet's disc to the area of the star's disc:

$$\frac{A_{planet}}{A_{star}} = \textbf{Percentage of Light Blocked}$$

Or, in terms of radius:

$$\frac{r_{planet}^2}{r_{star}^2} = \textbf{Percentage of Light Blocked}$$

The justification for this comes from a purely geometric argument. If a quarter of the light is blocked out, the planet covers one quarter of the star. Since we observe these things as two-dimensional projections, we use the area of each.

Astrometry

Contrary to the observations of ancient astronomers, stars are not fixed in place. Our own sun orbits around the center of our galaxy once every 230 million years or so. Considering a Newtonian picture of gravity and the fact that our sun is not, in any way, fixed in place, we can examine how its motion is influenced by the presence of planets.

Newton describes gravity as a force between bodies that have mass, and we describe the orbits of planets as a consequence of their gravitational attraction to the sun. From the students' perspective, this is all done with the tacit understanding that the position of the sun is fixed relative to the planets. In reality, however, the sun also moves. Consider Newton's 3rd Law: If the sun pulls on the planets via gravity, the planets must also pull on the sun via gravity. Forces cause accelerations, and therefore the sun ought to move. Granted, the sun's mass is so large that its motion is small compared to that of the planets, but it does wobble and this wobble can be measured.

If we were to look for this wobble, what would we find? Consider a system that is only one star and one planet, gravitationally bound to each other. They will orbit around a common center of mass, called the *barycenter*. If the two bodies are of near equal mass, like in a binary star system, the barycenter will be near the halfway point between the two stars. As the difference in mass between the two bodies increases, however, the barycenter moves toward the larger body. For many star-planet systems, the barycenter will be within the radius of the star, causing the star's motion to appear as a wobble, instead of as an orbit.

In principle, if this wobble can be observed, it serves as evidence that there are planets nearby. The period of the wobble is the same as the orbital period of the planet and the size of the wobble could be used to determine the mass of the planet. In fact, this effect is what is guiding the search for the as-yet-undiscovered "planet nine." In actuality, however, this technique is not extremely useful. The reason is because these wobbles are extremely small in star-planet systems. So small, in fact, that the maximum angular displacement that we would observe is around 50 times smaller than anything the Hubble Space Telescope could detect!

Radial velocity

Building upon the astrometry method, it's important to realize that while current telescopes may have limitations in their angular resolution, they are extremely good at measuring the wavelength of the light that comes in. So good, in fact, that they can measure a Doppler shift in that light if the star is moving just 1 meter per second toward or away from us. If you record the wavelength of light coming from a star and plot it as a function of time, sometimes you will find that it is periodic, because the change in wavelength is caused by a periodic wobble in the star's position. The period of this change tells you the period of the planet orbiting the star and the magnitude of the Doppler shift can tell you the speed of the star, which can tell you the mass of the planet.

For our students, an introductory mechanics course doesn't typically do a great job of considering orbits that are highly eccentric, but we do cover uniform circular motion with sufficient depth to come up with an acceptable approximation. Starting with Newton's 2nd Law for a planet undergoing uniform circular motion due to the force of gravity:

$$F_g = m_{planet} a_c$$

Substituting Newton's Law of Universal Gravitation and centripetal acceleration:

$$G\frac{m_{planet} m_{star}}{r^2} = m_{planet}\left(\frac{v_{planet}^2}{r}\right)$$

Recognize that the velocity of the planet is equal to the circumference of the circle it travels on divided by the period of the orbit:

$$v_{planet} = \frac{2\pi r}{T}$$

Rearrange for orbital radius:

$$r = \sqrt[3]{\frac{T^2 m_{star}}{4\pi^2}}$$

From this equation, the orbital radius can be determined from the measured period, once the mass of the star has been inferred by examining its emission spectrum. It's worth pointing out that you can use Newton's correction to Kepler's 3rd Law and the approximation that a planet's mass is very small compared to a star's mass to arrive at precisely the same result.

Using conservation of linear momentum, we can determine the mass of the planet. Because we assume the only forces acting on the star and planet are their mutual gravitation, the total linear momentum relative to the center of mass must be zero. To say that differently, the magnitude of the star's momentum must be equal to the magnitude of the planet's momentum:

$$p_{star} = p_{planet}$$

$$m_{star}v_{star} = m_{planet}v_{planet}$$

Substituting for the velocity of the planet as above:

$$m_{star}v_{star} = m_{planet}\left(\frac{2\pi r}{T}\right)$$

Rearrange for the mass of the planet:

$$m_{planet} = \frac{m_{star}v_{star}T}{2\pi r}$$

You can carry over the information from before regarding the mass of the star, the period of the planet's orbit and the orbital radius. The velocity of the star can be determined from the magnitude of the Doppler shift. Once you have the mass of the planet, if you have transit data, you can combine this with the size of the planet to determine the planet's density, which will tell you if it is gaseous or terrestrial.

The problem with this method comes from the measurement of the velocity of the star. If we're lucky enough to observe orbital plane of the system edge on, then there ought to be no issue. Unfortunately, the orbital planes of other solar systems are distributed more or less randomly around us, leading to this relationship between observed and actual velocities for stars:

$$v_{observed} = v_{actual}\cos\theta$$

Since the actual velocity of a star is always larger than the observed velocity, we can only ever determine a lower bound for the mass of the planet. If the planet transits in front of the star, it will restrict the potential error on this measurement, letting us know the measured mass is accurate.

Gravitational Microlensing

Gravitational microlensing is the least intuitive of the five techniques, because it requires an understanding of Einstein's description of gravity. In General Relativity, gravity is not a force, but a curvature of space and time near collections of mass and energy. What we perceive as a force is really just objects following the curvature of space-time. Consider the donation bins that have you rolling coins down a parabolic "drain." The coins will circle and circle, eventually falling into the collection bin below – this is somewhat similar to how objects move in curved space.

The microlensing part comes from the fact that light will also follow the curvature of space-time. As a planet passes in font of a nearby star, it will bend light from the star, potentially causing it to appear brighter by “focusing” the light toward our telescopes as a magnifying glass might. This is relatively rare, but also somewhat easy to observe. There is an extremely good animation of this on NASA’s exoplanet website that should make the concept relatively clear to students.

Life Beyond our Solar System

Once you start to look for planets beyond our solar system, students always want to know about aliens. Is there other life out there? Are we alone? Is there another planet we could live on? All things considered, there is more than likely life out there somewhere. Scientists have been able to find thousands of exoplanets in our relative neighborhood, and we are merely one of many galaxies. Even if a miniscule fraction of the stars in the universe have potentially habitable planets, there are so many stars in the visible universe that at least one of those planets near one of those stars ought to have life on it. The follow up, however, is that if we can find some sign of life, our chances of getting anywhere near it are essentially zero. The fastest man made craft, Juno, has traveled at about 100,000 meters per second. The nearest star, Proxima Centauri, is over 4 light years away. Traveling at Juno’s speed, it take over 12,000 years to get from earth to Proxima Centauri. To put that into perspective, the pyramids at Giza are only about 4500 years old.

While making contact with life or arriving at a habitable planet seem extremely far fetched now, that doesn’t mean that our search for life and discoveries of exoplanets out to end. When we think about what we might look for in a potentially habitable planet, there are essentially three things scientists look for. The first is planetary density. Simply put, if the planet is made of gas, there probably isn’t life there. Using the radial velocity and transit data we discussed before, it’s relatively simple to determine if a planet is terrestrial or gaseous by just computing the density.

The second thing scientists want to see is if the planet exists in a “habitable zone” near a star. What they’re looking for is the “Goldilocks” scenario. Is the planet too hot, too cold or just right? From our limited experience studying life on planets, we expect that liquid water is a necessary component for life – so if the temperature range where a planet is could support the presence of liquid water, we say it is within that star’s habitable zone. Depending on the size and temperature of a star, the habitable zone can be a closer or farther from the star. The spectrum of the star can tell you the where the habitable zone for it ought to be.

Finally, scientists look for an atmospheric composition that contains pieces we assume are necessary for life, like atmospheric oxygen, carbon dioxide and water vapor. Given our current telescopes, determining if these atmospheres are present is nearly impossible. That said, given better instrumentation, the measurement is simple to take. Remembering back to chemistry, different substances have different absorption spectra, meaning that a cloud of a particular gas will not allow certain wavelengths of light to pass through it. If, during a transit event, a telescope could measure the small dips in particular wavelengths of light, it could determine the composition of the atmosphere surrounding a planet. In certain scenarios, these measurements are already possible. In addition, future telescopes will have the required level of precision, so measurements like this will become commonplace in the relatively near future.

Objectives

The Objectives of the unit can be broken into two broad categories: qualitative and quantitative. When considering searching for exoplanets, students should have a qualitative understanding of each of the five techniques. Given data, students should then be able to quantitatively determine the mass and orbital distance of an exoplanet using techniques from classical mechanics. These are the main "physics" skills that go into this unit.

Once students have "found" exoplanets, they should be able to qualitatively discuss the signs of habitability that scientists would look for when trying to determine the nature of an exoplanet. Quantitatively, they should calculate the density of planets to determine if they are terrestrial and use materials to determine if a planet's orbital radius is within the habitable zone of a star.

Finally, to extend the unit further, students should have a qualitative understanding of the instrumentation scientists have and would need to make the observations necessary to confirm these signs of life. Students should also have a sense of distances and potential travel times within our own solar system and to these exoplanets. The last objective would be for students to connect some of their prior knowledge of biology to discuss how life on another planet might evolve, given the planet's density or atmospheric conditions. Some of this discussion would be purely speculative, but it would also be based in understandings the students have about the world they inhabit.

Strategies

The three main focuses of this unit are going to be having students make connections to previous scientific content, learn data analysis techniques and having students construct scientific arguments evidence. Once students can see that the little bit of introductory physics, chemistry and biology they've learned has enormous applications, it's my hope that they'll be more excited about following scientific news and pursuing careers in science. Because scientists have made this exoplanet data public, I want my students to learn to analyze data. My students already have some familiarity with Excel, and it is my hope that they will be able to continue to develop their familiarity with large data sets. I want to incorporate class discussion and some argumentative writing with this unit.

Drawing Connections

On one hand, a course in introductory mechanics is extremely limited. On the other, it can, in approximation, explain an enormous number of otherwise obtuse phenomena that our students can observe in the real world. By applying what they learn about classical mechanics to a real and current research problem in physics, students will start to realize they can use the physics they learn in class to solve problems beyond those presented in their textbook.

Data Analysis

The challenge with having students analyze data is deciding *how* they will analyze the data. Programs like Google Sheets and Excel are extremely common, regardless of the field a student eventually winds up in, but some of their analysis tools and packages are limited. For this unit, I advocate for students using LoggerPro, for two reasons. First, LoggerPro has built in curve fitting of periodic functions, which is necessary for determining the period of the radial velocity data. Second, LoggerPro has an extremely generous site license, making acquiring it relatively inexpensive. Students are free to install it on their personal computers and it can be added to any (non-Chromebook) in your school.

Committing to using LoggerPro if you don't already, however, has some challenges. The first is that students will need to be trained in the basics of the software. I find that a clear stepper sheet for some of the common tasks they might use is extremely helpful and can preempt a number of headaches.

Argumentation

Claim-Evidence-Reasoning is a commonly accepted format used to teach effective argumentation in the science education community. When students make claims about the data they analyze, I want them to identify the evidence that brought them to that claim and the reasoning that connects the two. Focusing on this particular format will give students the necessary tools and framework to better explain themselves in class and be more confident in their assertions.

Classroom Activities

Activities for this unit are based around using classroom experiments to recreate the techniques used by scientists to observe and identify exoplanets. As students become more comfortable with the techniques, they should progress to using actual data to recreate some of the existing exoplanet discoveries in the classroom. As a final project, students will conduct a habitability assessment of a few different exoplanets with the idea that they are advising a government agency about the likelihood of future colonization.

Radial Velocity Experiment (3 Days)

Using a ball attached to a string with a speaker inside, the effect of the orbital plane of planets on the observed shift in light color from a star can be investigated. First, as a exploration, have foam ball with a speaker inside emit a constant frequency of sound. Give these to students and have them qualitatively describe how changing the length of the string, period of the ball or the orientation of the plane in which it spins effects the sound they hear.

After students have had a chance to qualitatively explore the Doppler shift, they should quantitatively do it. Instruct students to perform trials where vary the length of the string, period of rotation and angle of inclination of the ball's motion and, using a Vernier Microphone and LoggerPro, plot frequency versus time for their trials. From this data, they should measure the orbital period of the ball as well as the maximum velocity of the ball. From their data, they should be prepared to discuss what effect each of the variables has on their results. Make sure to pay special attention to how the tilt of the plane of motion changes what they observe. To further drive this point home, you could swing a ball around and have students measure the same motion with the microphones tilted at different angles and compare the data.

Search for an Exoplanet (3 days)

Now that students have some experience doing the type of analysis that goes into radial velocity calculations, they should take a shot at trying to "find" an exoplanet. Using the data sets at exoplanets.org, first isolate some planets that have already been discovered using the radial velocity method that have low-eccentricity orbits. You can do this using the dropdown menu in the upper left on the data table and selecting "RV Planets." Download Radial Velocity graphs (for example, HAT-P-27 b) and have students determine the orbital periods. Gather information about each of the stars and supply students with an approximate mass, so that they can determine the orbital distance of each planet. Then, from the radial velocity graph, have students determine the mass of the planet. It's important to go through the data first, because not every entry on their database has a radial velocity curve attached to it. Furthermore, some of them have difficult to understand units on the time axis.

When looking for planets in the database, it's helpful to use the dropdown menu in the top left to also limit your search to transit planets, and look for planets that appear in both the RV and transit lists, so students can determine the size and density of each planet they explore.

Habitability Assessment (2 days for work, 2 days for presentations)

In this activity, students will be grouped into evaluation panels and supplied with some data about planets that have been identified by other researchers and asked to decide whether or not they think the planets are habitable. The planets will have a variety of characteristics provided, including information about the stars they orbit and their distances from them, information about atmospheric absorption lines, sizes of planets, density and the relative distances of each solar system from our own. For this activity, it's helpful to provide all of the necessary orbital parameters instead of having students do the analysis themselves. This shifts the focus from the quantitative work of searching for exoplanets to the qualitative work of evaluating their habitability.

Students will use the Claim-Evidence-Reasoning format for scientific argumentation in order to construct habitability assessments, framed as government reports, about each of the planets. In the end, students find out that the reason they were contracted for this evaluation is because they need to write a recommendation on what planet we should attempt to colonize. Sticking with the Claim-Evidence-Reasoning model, students will rank the planets and attempt to justify which one seems like the best option for colonization. A good way to evaluate their work is having them do presentations with question and answer sessions afterwards. You could give each group three planets, for example, and then have all of the groups come together and come to consensus on who has found the best choice for future colonization.

Bibliography

Teacher Resources

Assessments of Argumentation in Science. <http://scientificargumentation.stanford.edu/rationale/> The homepage of the Stanford Scientific Argumentation Group, with resources and assessment items for science teachers looking to build a culture of argumentation in their classroom.

Astrobiology. <https://astrobiology.nasa.gov/> A NASA resource on astrobiology with resources related to recent research on topics like life detection.

Claim Evidence Reasoning. <https://www.edutopia.org/blog/science-inquiry-claim-evidence-reasoning-eric-brunsell> An extremely basic, but effective introduction to the Claim-Evidence-Reasoning format for argumentation in science classrooms.

Exoplanet Exploration. <https://exoplanets.nasa.gov/> NASA resource dedicated to exoplanets and their detection with resources for both teacher and student.

LoggerPro. <https://www.vernier.com/products/software/lp/> Probably the best analysis software package available for high school and undergraduate science with an extremely generous site license where you can purchase the software for your school and every student and teacher can install it on their personal machines in perpetuity. Their website contains tutorials and resources for using LoggerPro in your classroom beyond just this unit.

NASA Exoplanet Archive. <http://exoplanetarchive.ipac.caltech.edu/> A searchable catalog of scientific data related to exoplanets and their discovery that can be used to provide students with real data for in class analysis.

Standards

PA Standards

- **3.2.P.B1.** Differentiate among translational motion, simple harmonic motion, and rotational motion in terms of position, velocity, and acceleration. Use force and mass to explain translational motion or simple harmonic motion of objects. Relate torque and rotational inertia to explain rotational motion.

- **3.2.10.B1.** Apply Newton's Law of Universal Gravitation to the forces between two objects.

Common Core Standards for Science and Technical Subjects

- **CC.3.5.11-12.A:** Cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the author makes and to any gaps or inconsistencies in the account.
- **CC.3.5.11-12.C:** Follow precisely a complex multistep procedure when carrying out experiments, taking measurements, or performing technical tasks; analyze the specific results based on explanations in the text.
- **CC.3.5.11-12.H:** Evaluate the hypotheses, data, analysis, and conclusions in a science or technical text, verifying the data when possible and corroborating or challenging conclusions with other sources of information.
- **CC.3.6.11-12.B:** Write informative/explanatory texts, including the narration of historical events, scientific procedures/ experiments, or technical processes.
- **CC.3.6.11-12.C:** Produce clear and coherent writing in which the development, organization, and style are appropriate to task, purpose, and audience.
- **CC.3.6.11-12.H:** Draw evidence from informational texts to support analysis, reflection, and research.

Common Core Standards for Mathematical Practice

- **MP3**: Construct viable arguments and critique the reasoning of others.
- **MP5**: Use appropriate tools strategically.
- **MP6**: Attend to precision.

Next Generation Science Standards

- **HS-PS2-1.** Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.
- **HS-PS2-4.**Use mathematical representations Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.