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Planetfinder: An Online Interactive Module for Learning How Astronomers Detect Extrasolar Planets

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Abstract

Planetfinder is a Web-based module designed to enable undergraduates to learn how astronomers detect extrasolar planets through observations of the Doppler shifts of a star's spectral lines. The module guides students through the process of measuring the masses and orbital parameters of actual extrasolar planets by fitting model Doppler curves to the data. The main goal of the exercise is to give students an understanding of the process of scientific measurement and model fitting. The exercise can be done at various levels of difficulty, ranging from measuring the properties of planetary systems having nearly circular orbits without using algebra, to exploring properties of systems having eccentric orbits and the associated equations of motion. The module is self-checking. Student work is stored in a database that is easily accessible by the instructor. The module has been tested at several institutions and is available for public use.

1. INTRODUCTION

Our modern understanding of the Solar System began circa 1570 with Tycho Brahe's observations of planetary motions, which were precise enough to expose flaws in the Ptolemaic model. Then, in 1619, Johannes Kepler showed that Tycho's observations could be fit with a heliocentric model in which the planets moved according to the following three laws:

1. The planetary orbits are ellipses.
2. The planets sweep out equal areas in equal times.
3. The orbital periods obey the relationship $P^2 \alpha a^3$, where a is the semimajor axis of the orbit.

Kepler’s great contribution was an inspired fit to the data. As far as we know, he had no idea of the concept of universal gravitation. He did, however, believe that natural phenomena could be described by mathematical models, a notion that can be traced back to Pythagoras (Koestler 1959).

Another 68 years passed before Isaac Newton showed that Kepler’s laws followed from his law of universal gravitation. In the meantime, Galileo had provided two major clues: his theory of inertia and his observation that the moons of Jupiter obeyed Kepler’s third law.

This story is typical of the way that scientific progress is usually made. With improved technology, scientists obtain data that do not fit the current paradigm, and then they analyze the data and find that they can be fit with equations, or "laws." Typically, the last step is for scientists to find a theory that explains the laws.

But this is not the way that students usually learn about planetary motions. Instead, they are first told about Newton’s theory of universal gravitation and how gravity provides the centripetal force necessary to account for the departures from inertial motion manifested in circular (or elliptical) orbits. Then, with a little algebra (or calculus), Kepler’s laws pop out.

This sequence runs exactly opposite to the way that scientists actually learned about planetary motions. It is what I call, "So there physics." Physics is codified in a set of laws, and with a little algebra, the student can verify that the laws can explain observed phenomena. So there! In this way, physicists come across as high priests who have privileged knowledge of the basic laws that govern all phenomena. The students do not learn the processes by which the physicists found the laws; as far as the students can see, the laws may have been carried down from a mountaintop on a stone tablet.

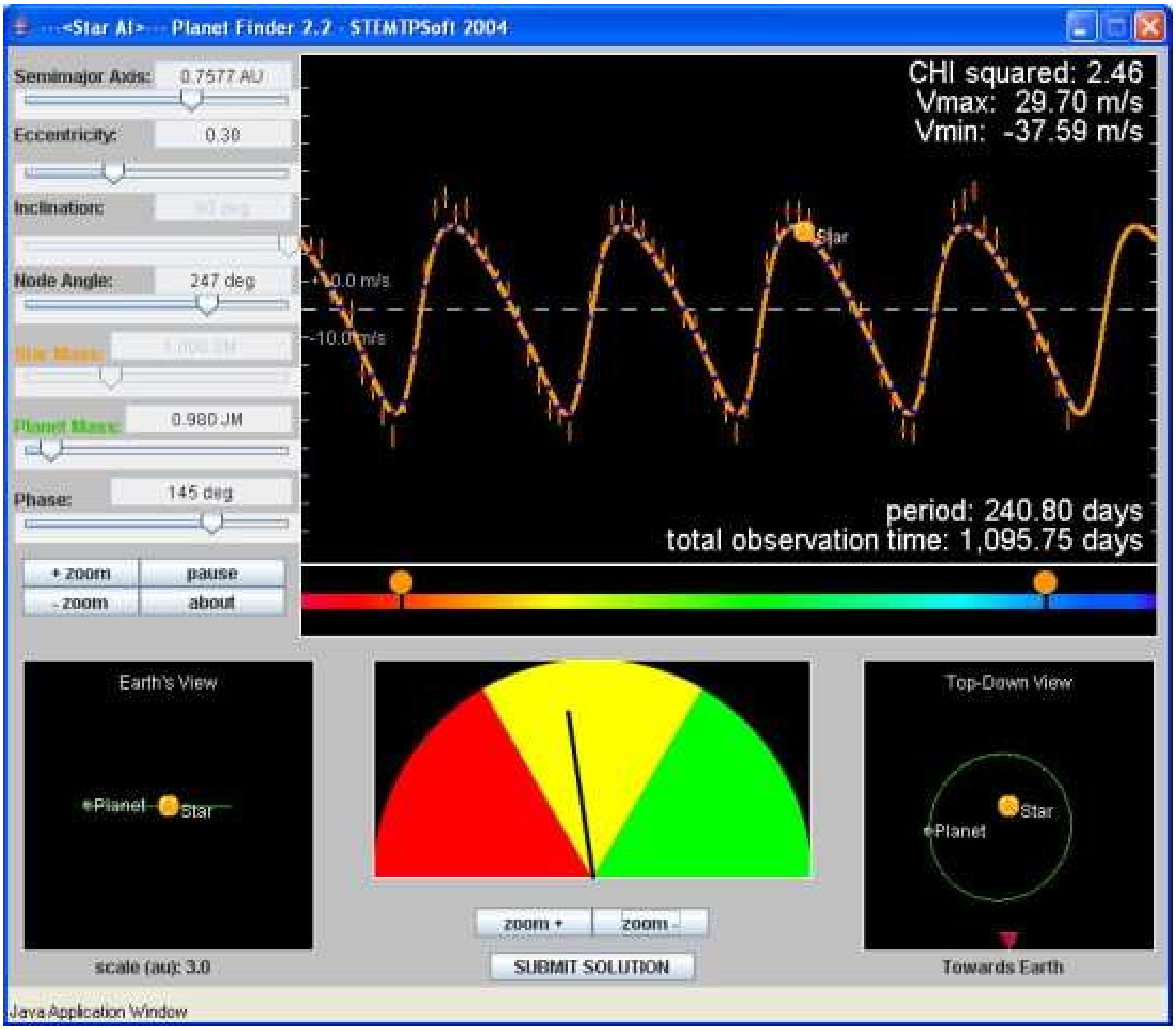
2. THE PLANETFINDER LEARNING MODULE

We have developed a learning module, called Planetfinder (http://stem.colorado.edu/planetfinder/instructor.html), that is intended to give students an opportunity to learn the properties of planetary orbits in the way that scientists actually did. Planetfinder consists of a series of carefully scaffolded exercises that lead students to understand the properties of planetary orbits and the strategies used by astronomers to discover extrasolar planetary systems.

Planetfinder has three major learning goals:

1. To visualize and understand how the planetary orbit manifests itself in the observed Doppler velocity curve
2. To understand how scientists determine properties of a model system by fitting a representation of the model to observed data
3. To understand how uncertainties in measurement determine the level of confidence of conclusions that can be drawn from the data

Planetfinder is built around a Java applet (Figure 1) that displays the orbit of an extrasolar planet, and the Doppler shift of the spectral lines of the star it orbits. (Several such applets are available online by clicking the link "Extra-solar Planets" at http://stem.colorado.edu/applets.) The student can manipulate all parameters determining the orbit—the masses of the star and planet, the semimajor axis, inclination, eccentricity, and node angle of the orbit—and can measure how these parameters determine the period, amplitude, and shape of the model curve representing the Doppler shifts in the star's spectrum that are due to its reflex motion.



Semimajor Axis: 0.7577 AU

Eccentricity: 0.30

Inclination: 90 deg

Node Angle: 247 deg

Star Mass: 1.000 SM

Planet Mass: 0.980 JM

Phase: 145 deg

CHI squared: 2.46
Vmax: 29.70 m/s
Vmin: -37.59 m/s

period: 240.80 days
total observation time: 1,095.75 days

Figure 1. The graphical interface of the Planetfinder applet. The orange curve represents a model of the Doppler shift of absorption lines in the companion star's spectrum, which is illustrated schematically in the rainbow below the graph. The sliders control the orbital parameters of the model curve. The user sees two views of the planetary orbit: the top-down view on the right, and the Earth's view on the left. The user sees the absorption lines of the star shift from red to blue and back again, while the orange dot dynamically traces out the graph of the Doppler shift as the planet orbits the star. The game for the user is to manipulate the parameters of the model orbit until the model curve is a good fit to the data points. The goodness of fit is represented by the meter in the bottom center, which is coupled to the value of $X^{2/}$(d.o.f.), displayed in the upper right.

In the Planetfinder module, the students are led, step by step, through a set of exercises, with the applet guided by a set of questions that they can answer online. The students are not given any equations to manipulate; instead, their job is to observe the orbit and to measure how the Doppler curve of the star depends on the orbital parameters.

Many students taking introductory science have trouble coping with unfamiliar vocabulary—terms such as "semimajor axis," "parameter," "orbital period," "Doppler shift," and so on. To mitigate this problem, the module provides a student with the opportunity to see a definition of any such term in the text by simply selecting the term with the mouse pointer.

Students submit all their answers to a database via online forms. Students must enter answers to every question on each page before proceeding to the next page. The exercise is self-checking: if the student attempts to submit numerical or multiple-choice answers that are not in the correct range, the page will kick back with red X-marks next to each wrong answer. Then the students can correct their answers and proceed.

In addition to the questions requiring numerical or multiple-choice answers that can be checked automatically, Planetfinder contains questions that require brief written answers. The students enter their answers in text boxes, which are captured in a database.

We believe, following Alavi (1994), Cohen (1994) and Dillenbourg (1999), that many students learn best if they work in small groups (say, two or three students for each computer terminal). Planetfinder is designed to facilitate such collaborations. The login procedure permits up to three students to sign up to do the exercise as a group. However, any student can choose to complete the exercise individually.

3. FITTING DATA

In addition to displaying the Doppler curve resulting from the orbital parameters that the students control, the Planetfinder applet also displays a set of data representing the star's measured Doppler curve. They are actually pseudo-data, generated with a random number generator, having properties (cadence, duration, rms error, and orbital parameters) that are very similar to actual observations of a star in an extrasolar planetary system. The students' task is to manipulate the parameters so that the model curve fits the data.

The process of fitting a model to the data introduces the students to another aspect of the scientific method—namely, how scientists deal with uncertainty. This process, so fundamental and universal to all science, is another one that "so there" physics fails to address. We think that if students taking an introductory science course remember only one lesson throughout their lifetime, it should be this: All scientific conclusions are based on measurements, which are inherently uncertain; therefore, we can only "know" a scientific "fact" with a level of confidence that depends on the quality of the measurements.

Part 1 of Planetfinder guides the students to find a best-fit model to data representing an actual planetary system having a nearly circular orbit. As students manipulate the applet to fit the model curve to the data, they can watch a meter (Figure 1) that represents goodness of fit, as determined by chi-squared/(degree of freedom). The needle in the meter enters the yellow zone when $X^{2/}$(d.o.f.) < 3 and enters the green zone when $X^{2/}$(d.o.f.) < 1.5. The value of $X^{2/}$(d.o.f.) is displayed in the upper right-hand corner of the applet, and the students are asked to note how it changes as they improve their fit. Without being told the statistical definition of $X^{2/}$(d.o.f.), they will see that it is a useful figure of merit that correlates with the quality of their eyeball fit.

We hope that once students see that a certain figure of merit is useful in solving a practical problem, they will be motivated to learn how such a quantity is defined. Therefore, in the lesson, we provide an icon with a little scuba diver urging the student to "Go deeper," which is linked to a page that defines $X^{2/}$(d.o.f.) and describes its properties.

When students find their best model fit to the data, they are asked submit the parameters of the fit to a database. But we want them to realize that the parameters defining the best fit of a model to a particular data set do not necessarily represent the best approximation to the actual system represented by the data. Therefore, we ask the students not only to find the best fit but also to find the upper and lower bounds of the parameters that provide acceptable fits.

When students have determined the range of acceptable fitting parameters, Planetfinder opens an external Web page to the Extra-solar Planets Catalog (http://exoplanet.eu/catalog.php), which provides the actual data of all known extrasolar planetary systems. They are challenged (and will succeed) to find the system having parameters that correspond to their model fit. They are invited to look at the actual data and will find that they look very similar to the pseudo-data that they have analyzed.

In Part 2, the students will use the same applet to analyze a different extrasolar planetary system (still with a circular orbit) having data of lower quality, either in orbital phase coverage or in uncertainty in the measurement of Doppler velocity.

In Part 3, the students compare their analysis results with those of 13 different planetary systems that have been analyzed by other groups of students. They are asked to compare the properties of the systems that they analyzed with the properties of other systems. Students see that each of 14 systems has been analyzed according to two data sets: one with good phase coverage and relatively small measurement uncertainty, and another that is more challenging. They are asked to explain why the better data set yields a model fit with more tightly constrained parameters and to consider how the choice of observing strategy—observation cadence, duration, and measurement errors—will limit the ability to detect extrasolar planets.

The list of planets that students will encounter in Part 3 is representative of the variety of planets actually discovered by the Doppler technique, so students learn why this technique is good for finding massive planets with relatively small semimajor axes but fails to find Earthlike planets.

A student who completes Parts 1–3 of Planetfinder will see that he or she has actually carried out a process almost identical to the process that research scientists used very recently (in some cases, a few months prior) in discovering and measuring the properties of extrasolar planets. Without studying the algebra of orbital mechanics, the student will have seen how the orbital period and velocity correlate with the orbital radius (semimajor axis) and how the reflex motion of the star correlates with the mass of the planet. He or she will also have learned how astronomers determine the mass and orbital period of the planet by fitting a model to the data and how the ability to measure these properties depends on the quality of the data. These learning goals may be sufficient for a student taking an introductory astronomy course. Therefore, we have designed the module so that the student may complete the exercise by jumping directly from Part 3 to Part 7, the final part of the exercise.

4. FEEDBACK AND REFLECTION

Part 7 of the exercise has two goals. The first is to capture feedback from the students on how they used Planetfinder (Solo or with a group? What kind of computer? Where? How long did it take them to complete Planetfinder ?) and on how they found the exercise (easy-difficult; confusing-clear; interesting-boring), and to ask for specific advice on how the exercise might be improved.

Second, we asked the students, "Please state, in rank order, the three most important lessons you learned from doing this exercise." The students submitted their replies to this question in text boxes. We believe that this simple request is one of the most powerful learning tools in the exercise. By simply requiring students to reflect on the significance of what they have learned, we are helping them to develop metacognitive skills. We are also providing invaluable feedback to the instructor (and to the designer of the module) as to whether the students are actually learning what we hope they will learn.

Finally, we asked students to provide feedback on their experience and to reflect on what they have learned. Generally, students felt that the exercise was challenging and worthwhile. In many cases, they verified our initial suspicion that students are not exposed to the notion of measurement as a scientific process. Indeed, one student expressed his view of science this way: "I knew all of the science presented in this exercise prior, however, physically fitting data and determining error was a new experience."

Most students got the main point of the exercise, as the following sample responses indicate:

> "I learned about error bars and how they affect the accuracy of the data. Large error bars lead to large percent error in your best fit, while small error bars can lead to a very good approximation. Also, I learned how the value of chi squared is relevant to error bars."
>
> "I enjoyed learning how astronomers find data concerning extrasolar planets using curve fitting. The process is tedious but it is amazing what can be learned off of a simple curve-fitting exercise."
>
> "I have learned that extra-solar planets are really only able to be detected when they are large enough and in close enough to their star to produce a wobble in the star that is pronounced sufficiently for it to be detected by instruments on Earth."

5. BEYOND THE BASICS

By working through Parts 1–3 of Planetfinder, students will learn the properties of circular orbits and how astronomers discover extrasolar planets by observing periodic Doppler shifts in the spectrum of the central star. Part 4 is designed to show the student that the mass of the planet inferred from a fit to the star’s Doppler shift data depends on the assumed mass of the star, which must be determined by other means (usually, the star’s spectral type). Part 5 is designed to show how the inferred planet mass, M, depends on the inclination, i, of the planet’s orbit, and in fact that the fit to the observed data can only determine the value of $M\sin i$.

Part 6 introduces the concept of eccentric orbits. In this part, the students learn to fit a model curve to data points for stars with extrasolar planets that are in highly eccentric orbits. In addition to sliders controlling the semimajor axis, phase of the orbit, and the planet mass, the applet has sliders by which the user can adjust the eccentricity and node angle of the orbit.

Planetfinder is designed so that students will observe and analyze the behavior of a physical system before they are presented with the "laws" governing that behavior. But of course, we want students ultimately to see how these laws are codified in a theory that can be expressed mathematically. Therefore, all the relevant theory and a few examples are embedded in the module and can be accessed by clicking "Go deeper" scuba diver icons that are placed at appropriate places throughout the text. Students who wish to see the theory can do so at any time by clicking on these icons. However, we suggest that students skip over these icons during their first pass through the lesson and return to the theoretical interpretation only after they have gained a sense of the behavior of the system.

6. FACILITIES FOR THE INSTRUCTOR

We have designed Planetfinder to be "instructor friendly." Accordingly, we provide complete documentation and advice for instructors. The instructor can create an online session for his or her class, with a unique name and password to retrieve student data. Students can enter the named session and set their own passwords to retrieve or resume their own work. All student answers are entered into a database, which the instructor can view and download in convenient formats.

The module also contains help links by which any student can inform our Webmaster of any problems, technical or otherwise. We will respond rapidly to any such notification.

After the students have completed their work and the instructor has downloaded their work and scores, Planetfinder automatically sends the instructor a brief questionnaire soliciting his or her advice about how the exercise went, how the students responded, and how to improve the module. Thus, we have embedded feedback loops to capture information on student learning, student attitudes, and the advice of instructors. These feedback loops will enable us to continue to refine the module and also will give us valuable information that we can use in designing other such modules.

Planetfinder has undergone extensive field testing and revision. Several instructors have used it in introductory astronomy courses at the University of Colorado, and we have tried it out with a group of high school science teachers at a summer workshop. We have also demonstrated Planetfinder at an educational workshop held during the American Astronomical Society annual meeting, and instructors at a few other universities and colleges have beta-tested earlier versions of the module. In November 2005, we demonstrated the applets and the module at an international workshop on undergraduate science education in Wuhan, China. The workshop was sponsored by the Chinese Ministry of Education and Project Kaleidoscope (http://www.pkal.org/). Subsequently, a faculty member at Nanjing University used it in his introductory astronomy class.

We believe that Planetfinder is ready for general use. We hope that this article will encourage readers to try it with their classes. To do so, just open the site (http://stem.colorado.edu/planetfinder/instructor.html) and follow the instructions. The first time you try it with your class, please use it as it stands on our server at the University of Colorado so that we can ensure that the program is working properly. If you wish to run Planetfinder on your local server after using it once and providing feedback to us, we will be happy to enable you to download the entire program to your local server.

7. FINAL THOUGHTS

Many studies (e.g., Finkelstein et al. 2006) testify to the power of simulations for improving student learning and conceptual understanding. A search on the Web (see, e.g., http://merlot.org and http://compadre.org) will yield many animations and simulations, applets or Flash, that can be very effective for visualizing and understanding physical systems. However, to be effective learning tools for all students, these devices must be embedded in lesson plans or learning modules that guide the students toward clearly defined learning goals (Clark & Mayer 2003). de Jong and van Joolingen (1998) succinctly stated the principles that should guide the design of such modules:

> Three individual instructional measures can be seen as measures that have the promise of having a positive influence on learning outcomes. First, providing direct access to domain information seems effective as long as the information is presented concurrently with the simulation so that the information is available at the appropriate moment. Secondly, providing learners with assignments (or questions, exercises, or games) seems to have a clear effect on the learning outcome. Thirdly, learners who use an environment that includes model progression perform better than learners using the same environment without model progression, though it seems that the model needs to be sufficiently complex to reach this effect. (195)

Planetfinder is intended to demonstrate how this can be achieved. We hope that it will serve as a prototype for other such learning modules. In fact, it was much easier to design and develop the Planetfinder applet than it was to design the Planetfinder learning module. We believe that it is impossible to design an effective learning module without incorporating feedback loops in the design process (Wilson & Daviss 1996). These loops include the use of focus groups and facilities for capturing student and instructor feedback that are embedded in the learning module itself.

Because it is Web based, Planetfinder can be used in a pure distance-learning mode. However, we think that it and other such learning modules are most effective if used in a hybrid mode that involves both distance learning and face-to-face learning. For example, we advise instructors first to demonstrate the Planetfinder applet in class, and then to arrange scheduled sessions in a computer lab where students can interact with each other and receive help and encouragement from others who know the module well. In our experience, trained undergraduates can fill this role very well. Finally, we encourage students to carry out this exercise in small groups rather than individually.

Acknowledgments

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