A demonstration setup to simulate detection of planets outside the solar system

2011 Phys. Educ. 46 554

(http://iopscience.iop.org/0031-9120/46/5/007)

www.iop.org/journals/physed

A demonstration setup to simulate detection of planets outside the solar system

W Choopan[1], **W Ketpichainarong**[1], **P Laosinchai**[1] **and B Panijpan**[2]

[1] Institute for Innovative Learning, Mahidol University, Thailand
[2] Faculty of Science, Mahidol University, Thailand

E-mail: scbpn@mahidol.ac.th

Abstract

We constructed a simple demonstration setup to simulate an extrasolar planet and its star revolving around the system's centre of mass. Periodic dimming of light from the star by the transiting planet and the star's orbital revolution simulate the two major ways of deducing the presence of an exoplanet near a distant star. Apart from being a visual aid for those needing help, the setup also elicited unexpected questions and suggestions from students, who achieved a fairly good level of understanding of the basis for the transit and radial velocity methods.

Introduction

Students are generally intrigued by news of the Earth-based or satellite-based detection of yet another exoplanet (a planet outside our solar system) probably because of the possibility of there being Earth-like ones that are habitable [1], e.g., ones with rocky composition and size similar to K-11b found by the Kepler Telescope [2].

The more inquisitive ones may ask how one could prove the existence of such non-luminous objects so far away [3]. We at first thought that it would suffice to just show these university students static sketches of a setup equipped with a highly sensitive light detector (complementary metal oxide semiconductor or charge-coupled device) pointing at a particular part of the sky which should be able to detect the dimming of a star whose light is blocked periodically by an orbiting planet passing (transiting) the light path. While some students quickly accepted our explanation of the transit method, made possible by periodical blocking of the star's light, others could not 'see' how it could be done. We thus made a simple (first version) simulation setup (for the transit method), which proved more useful than just being a physical aid to ease the burden of imagination.

The demonstration setup

In spite of the simplicity of the first version setup, questions arose that did not arise with the static sketches, for example, 'What if the rotating planet did not block light along its path to the detector?' and 'How can one determine the size of the planet?'. But the setup had to be improved because it did not adequately address the radial velocity method of detection, quite a fruitful way of showing up exoplanets. We were fortunate to have been advised by an expert to come up with the simulation setup described below. In this setup, a hollow translucent plastic sphere (7.5 cm) with a light bulb inside acts as the star and opaque balls with diameters of 4 and 2.75 cm represent two exoplanets of different sizes but of the same mass (but different density). The sphere and one

0031-9120/11/050554+05$33.00

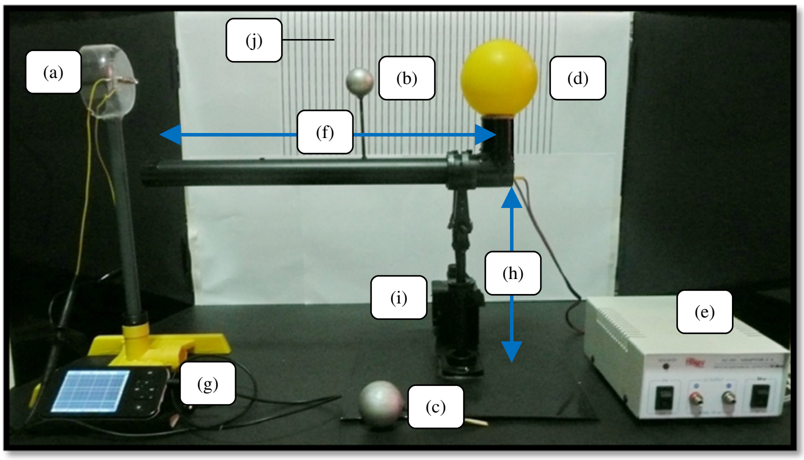


Figure 1. (a) Detector, (b) and (c) opaque balls with diameters of 2.75 and 4 cm, (d) hollow translucent plastic sphere, (e) power supply, (f) solid plastic tubing, (g) datalogger, (h) vertical arm, (i) motor, and (j) scale.

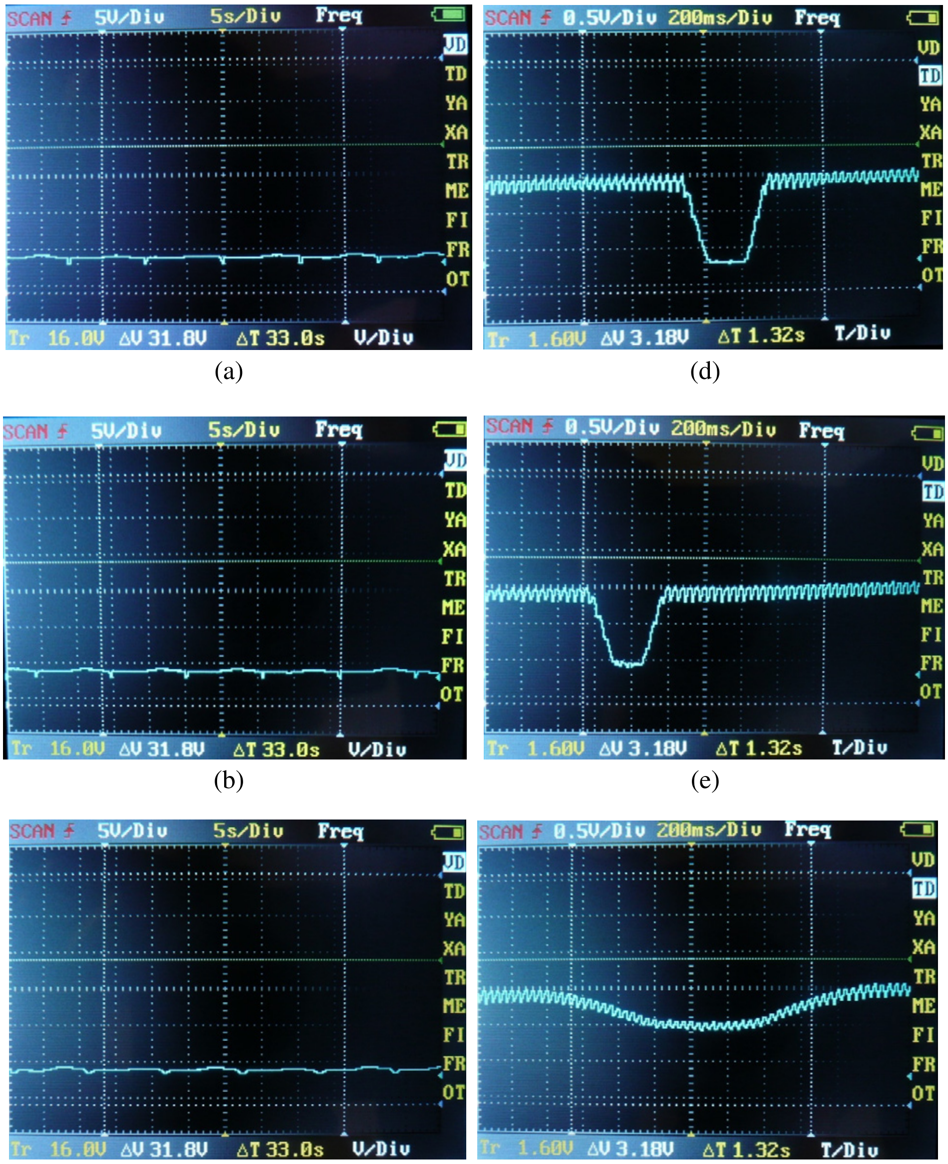
of balls are linked by a horizontally placed solid plastic tube which is in turn attached firmly and perpendicularly to a stiff vertical axis placed at the supposed 'centre of mass' of the two-object system. The 'centre of mass' can be moved along the tube depending on the relative mass of the star to that of the planet. The vertical axis is rotated by a motor leading to the rotation of both objects around the centre of mass. Periodically the ball (planet) crosses the light path from the plastic sphere (star) to the detector made up of eight photodiodes (each a silicon planar photodiode in a standard TO-18 hermetically sealed metal case with a glass lens) arranged horizontally and wired to the datalogger. The detector's voltage rises and drops according to the intensity of light impinging on it. The changing intensity is due mainly to the transiting of the ball (planet) moving past the plastic sphere (star). Recordings are made continuously by a datalogger, as shown in figure 1.

Results and discussion

When the planet (opaque ball) moved into the light path of the star (translucent globe) on its way to the detector, a drop in voltage of the latter could be recorded via the datalogger. While the planet was orbiting the star, a few students noticed that the star also visibly moved to and fro and sideways relative to the detector. The instructor then asked the students to try to exploit the change of the star's position for detecting a planet. Some students could come up with reasonable proposals for the star periodically approaching and becoming more distant: exploitation of Doppler spectroscopy or time-dependent fluctuation of light wavelength arising from the star going back and forth. The use of the spectral shift in the direction of detection due to the Doppler effect is called the radial velocity method, a popular way to detect exoplanets [4]. The students suggested an enhancement of this experimentally detectable toing and froing relative to the detector by having a static ruled scale placed in the background parallel to the line joining the star and the detector so that its approaching and becoming more distant with time could be seen or even measured more easily.

We also discussed the effect of the size of the planet on the brightness variation during the exoplanet's transit centrally across the star. Comparing the curves of figures 2(d) and (e), we found that the large ball (planet) could produce more dimming than the small ball but the duration of the drop in brightness for both light curves was the same because these two planets had the same orbital radius.

The lines in figures 2(a)–(c) demonstrate the variation in the brightness when the balls orbited around the bright sphere in five cycles. The shapes of these lines should strictly reflect the blockage of light. In fact, the actual data from detection of exoplanets by the transit method show only the dimming of light due to blockage because, for light coming from a distance of light years away, the change in intensity due to star oscillation cannot be as easily detected. Thus a detected change in baseline light intensity (no matter how slight) by



(a) (d)

(b) (e)

(c) (f)

Figure 2. Datalogger together with detector records of brightness change when an opaque ball (planet) with a diameter of (a) 4 cm or (b) 2.75 cm crosses the light path of the star (translucent sphere). The distance from the hollow translucent plastic sphere (star) to the opaque balls (planets) in (a) and (b) is equal to 34 cm. Note that the sizes of the balls in (a) and (c) are the same but for (c) the distance is 14 cm. Parts (d), (e) and (f) are zoomed (magnified) pictures of the light curves of (a), (b) and (c), respectively.

any setup in response to the to-and-fro movement of a star should be corrected. In our case, the baseline was 'flattened' somewhat by adjusting the sensitivity of the detector to match the intensity of the lamp, be it an AC or a DC type. One caveat is that the lamp's output (run off the mains using the same AC/DC power supply) should be allowed to stabilize before the demonstration, thus reducing the ripple in the traces. A battery-run DC lamp also works, but its output is usually lower.

Finally, we asked the students to compare the effects of the orbital radius of the planet on the duration of the transit by observing the lines shown in figures 2(d) and (f). The transit time should be inversely proportional to the orbital radius from the centre of mass of the celestial object. In other words the farther the planet is from the centre of mass the shorter the transit duration. In our case, the star should be seen to move closer to and further away from the observer relative to the scale in the background and the speed to and fro could be estimated with a speed tracker.

Because our setup could only show the forward and backward movement of the star relative to the scale (having the teeth of a comb) on the background, the students had to be told about the actual method of detection by the star's spectral shifts using Doppler spectroscopy. The extent of the spectral shift could be transformed into the radial velocity of figure A.1.

We realize that useful articles and helpful web-based information on exoplanets have been published [1–8] but none has proposed a physical setup(s) like ours, which incidentally has turned out to be more thought provoking than just perfunctory. However, our setup has limitations, e.g., the short distance (0.1–10 m only) between the star and planet does not reflect reality. The planet is unrealistically large compared to the star and our star does not rotate or turn around its axis. Yet we hope that other teachers will build a similar simulation setup(s) that will encourage students to reflect and learn more.

Acknowledgment

We thank Watchara Liewrian for assistance with the demonstration setup.

Appendix. Theory

Because a star wobbles in the presence of a planet(s), a spectroscopic detector can record the spectral shift of light arising from the Doppler effect due to the forward and backward movement of the star. These slightest of shifts to the blue and the red ends of the light (electromagnetic) spectrum can be used to calculate the radial velocity of the star orbiting the centre of mass (figure A.1). The orbiting extrasolar planet's mass can be determined from the change in the star's radial velocity. The amplitude (K) of the velocity versus time curve in (in figure A.1) can lead to the calculation of the planet's mass as shown below.

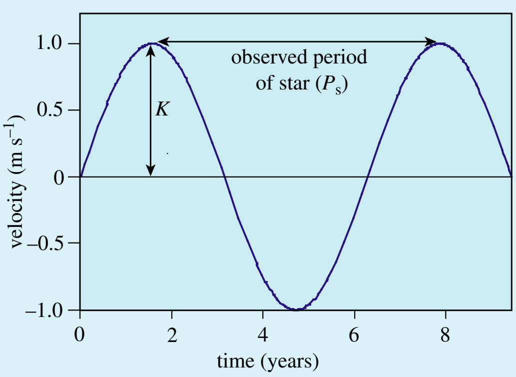


Figure A.1. The sinusoidal wave of radial velocity versus time as measured from Doppler spectroscopy.

Using Kepler's third law of planetary motion, the observed period of the star (equal to the period of the observed variations in the star's spectrum) can be used to determine the planet's distance from the star (r) by using the following equation:

$$r^3 = \frac{GM_\mathrm{s}}{4\pi^2} P_\mathrm{s}^2 \qquad \text{(A.1)}$$

where r is the distance of the planet from the star, G is the gravitational constant, M_s is the mass of the star, which may be assumed to be that of one (not too young or too old) on the main sequence of the Hertzsprung–Russell diagram [9], and P_s is the observed period of the star.

As we observe the change in the detected brightness of the star which is partially and periodically lowered by the exoplanet (figure A.2(a)), the curve of the dimming of light from the transit method (figure A.2(b)) can reveal information about the exoplanet such as size and orbital period.

The duration of the transit (t_tr) and the period of the transiting exoplanet (T_pl) are used by astronomers [10–12] to obtain the combined radii of the star (R_s) and planet (R_pl) by the equation (assuming the planet's orbit to be circular or close to circular)

$$t_\mathrm{tr} = \frac{T_\mathrm{pl}}{\pi}\left(\frac{R_\mathrm{s} + R_\mathrm{pl}}{r}\right) \qquad \text{(A.2)}$$

where r is derived from (A.1),

$$R_\mathrm{s} + R_\mathrm{pl} = \frac{\pi r t_\mathrm{tr}}{T_\mathrm{pl}}. \qquad \text{(A.3)}$$

The ratio between the radii of the exoplanet and the star $\frac{R_\mathrm{pl}}{R_\mathrm{s}}$ can be determined by the depth of the dimming (ΔL) of the detected light and the light from the unblocked star (L). For most stars

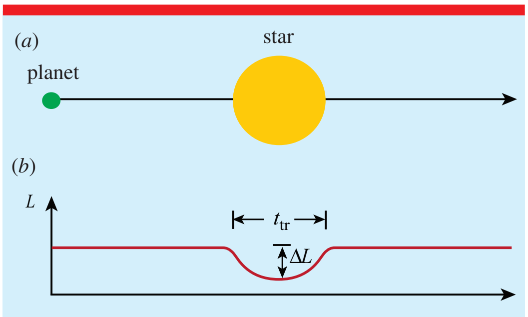


Figure A.2. Sketches showing (*a*) a star being transited by an exoplanet from left to right and (*b*) the detected light curve showing the dimming of the star caused by the exoplanet which centrally transits its star.

and planets, the relationship [10–12] between the relative amount of light dimming $\frac{\Delta L}{L}$ and the radii of the exoplanet and the star is given by

$$\frac{\Delta L}{L} = \left(\frac{R_{pl}}{R_s}\right)^2. \tag{A.4}$$

The star's and the planet's radii can be calculated by the relationships in (A.3) and (A.4): two equations with two unknowns.

Having determined r, the velocity of the planet can be calculated using Newton's law of gravitation and the orbit equation as given by

$$V_{pl} = \sqrt{GM_s/r} \tag{A.5}$$

where V_{pl} is the orbiting velocity of the planet.

The mass of the planet (M_{pl}) can be found from the calculated radial velocity ($V_s = \frac{K}{\sin\theta}$) (see figure A.1) of the star

$$M_{pl} = \frac{M_s V_s}{V_{pl}} \tag{A.6}$$

where θ is the inclination of the planet's orbit to the line perpendicular to the line-of-sight. The planet's density can be deduced from the calculated radius (R_{pl}).

Received 12 February 2011, in final form 24 April 2011
doi:10.1088/0031-9120/46/5/007

References

[1] Laughlin G 2010 A dance of extrasolar planets *Science* **330** 47–8
[2] Reich E S 2011 Beyond the stars *Nature* **470** 24–6
[3] Sasselov D D 2008 Extrasolar planets *Nature* **451** 29–31
[4] Schneider J 2011 http://exoplanet.eu/catalog.php (retrieved 12 Feb 2011)
[5] McCray R 2007 Planetfinder: an online interactive module for learning how astronomers detect extrasolar planets *AER* **5** 217–25
[6] Jet Propulsion Laboratory 2010 http://planetquest.jpl.nasa.gov (retrieved 19 Nov 2010)
[7] Prather E E and Slater T F 2001 Bringing extra-solar planets into the introductory physics classroom *Phys. Teach.* **39** 120–2
[8] LoPresto M C and McKay R 2005 An introductory physics exercise using real extrasolar planet data *Phys. Educ.* **40** 46–50
[9] Strömgren B 1933 On the interpretation of the Hertzsprung–Russell-diagram *Z. Astrophys.* **7** 222–48 (in English)
[10] Perryman M 2000 Extra-solar planets *Rep. Prog. Phys.* **63** 1209–72
[11] Schneider J 1999 The study of extrasolar planets: method of detection, first discoveries and future perspectives *C. R. Acad. Sci., Paris Serie IIb* **327** 621–34
[12] Deeg H J 1997 Photometric detection of extrasolar planets by the transit method *Brown Dwarfs and Extrasolar Planets* (*ASP Conf. Ser.* vol 133) ed R Rebelo *et al* pp 216–23

Wachiraporn Choopan is a PhD student in the Institute for Innovative Learning, Mahidol University, Thailand. Her main interest is in astronomy education.

Watcharee Ketpichainarong is a deputy director of the Institute for Innovative Learning, Mahidol University. She is a PhD graduate in science and technology education (Mahidol University) and is dedicated to bioscience education.

Parames Laosinchai is a lecturer at the Institute for Innovative Learning, Mahidol University. He is a PhD graduate in science and technology Education (Mahidol University). His specialty is mathematics education.

Bhinyo Panijpan is a former director of the Institute for Innovative Learning and currently affiliated with the Multidisciplinary Unit, Faculty of Science, Mahidol University. He is the holder of a PhD in molecular biophysics (University of London, King's College), and publishes in science and mathematics education journals.