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Article *in* Astronomy Education Review · December 2011

DOI: 10.3847/AER2011028

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Astronomy Education Review

2011, AER, 10, 010108-1, 10.3847/AER2011028

Using Smartphone Camera Technology to Explore Stellar Parallax: Method, Results, and Reactions

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Received: 09/14/11, Accepted: 12/5/11, Published: 12/22/11

Abstract

The use of a smartphone, with both still and video capabilities, to develop the concepts surrounding stellar parallax is described. The hands-on activities generate useful discussion amongst high school students. Reactions of both students and teachers are presented.

1. INTRODUCTION

Stellar parallax is a concept that is dealt with infrequently in the high school classroom other than by qualitative consideration of stereoscopic parallax and argument by analogy, such as that outlined in Zeilik (1998). The most common approach involves students being asked to view their finger held at arm's length and first viewing it from one eye and then the other. They "see" their finger's apparent movement against the background of the room. Following this qualitative approach, the unit of distance used in astronomy is introduced from a definitional point of view: "The parsec is the distance of an object at which the angle subtended by a baseline equal to the distance between the Earth and the Sun is one second of arc." This description is quite abstract, however, and it is unlikely that students will really get a conceptual feel for the idea of a *parsec* as a distance measure from an abstract mathematical statement. As the parsec is the fundamental unit of distance in astronomy, it is important that students have some strong insight to what this unit actually means (Marin 2010).

We assessed a sample of diagrams available on the internet using a Google Image search. The first 50 diagrams presented from the search term "Stellar Parallax" were examined. Out of the 50 diagrams, 18 showed the alternative conception that all stars in the night sky "wobble" in a straight line, a further 20 showed the special case, where the star is on the ecliptic equator where they actually do wobble in a straight line, and a further 7 had major faults. Only five out of the 50 diagrams accurately represented the relationship between the Earth–Sun orbit and the parallactic ellipse in the sky. That is to say, of this sample of 50 diagrams, only 10% could be considered to be scientifically accurate and a complete conceptual representation of stellar parallax.

The experimental determination of stellar parallax is seldom dealt with in the science classroom because the parallactic angle is so small. Students have little, if any, idea of how astronomers collect their data because they do not normally conduct the experiment first successfully executed by Bessel in 1838 in measuring the parallax of 61 Cygni. Hirshfeld (2001) presents a good summary of this discovery. That is to say, they cannot hold a protractor up to measure the parallax angle. Consequently, use of stellar parallax for distance determination can be difficult for students to understand without some type of hands-on experience to explore the concept. While students could undertake this project with a relatively small telescope and CCD camera setup such as that outlined in Ratcliffe *et al*. (1993), the time to acquire the observations (at the very least, six months) and the general availability of this equipment to the average classroom make this approach problematic.

Thus, the purpose of this paper is first to describe a practical, guided inquiry-based approach that uses smartphone camera technology to introduce stellar parallax to students in high school physics, and which is similar to the procedure suggested by De Jong (1972) using a Polaroid camera. This leads both students and teachers to understand the concept and, in the process, engages them actively in science. Second, we briefly present students' and their teachers' reactions to the laboratory exercise that indicate both a high level of engagement and a deep understanding of the methods used by astronomers.

2. THE APPROACH

2.1. Outline

Using a smartphone camera, or indeed a digital camera, the method for using parallax to determine distance can be introduced to the students. The method is relatively simple and uses the student's own camera, or their smartphone, a tool with which they are probably already very familiar and comfortable. Indeed, a smartphone with its megapixel camera and large screen is ideal because it allows measurements to be made directly on the camera screen. If an ordinary cell phone camera is used, or a digital camera, then the images have to be transferred to a computer and measurements made on the monitor. Thus, using a smartphone allows the practical to be completed in one class of approximately 40 min duration. Hereafter, only a reference will be made to the "smartphone."

The method simulates what actually occurs in astronomical research, albeit without complications such as the proper motion of the star or the parallactic ellipse (although we do provide a qualitative extension to demonstrate this.) The measurements yield student-friendly numbers, e.g., a baseline of a few tens of centimeters rather than 149.5×10^6 km, angles of degrees and minutes of arc rather than less than 1 arc sec, and an investigation lasting approximately one school science period rather than one that takes at least six months. Students can thus understand how astronomers measure the parallax angle and arrive at an understanding of the errors involved. Indeed, they can even understand the mathematics involved and appreciate the application of simple trigonometry. A major intent of this laboratory project is to equip the students with the conceptual knowledge and later to execute the method using real astronomical data.

2.2. Procedure

Students are introduced to the general idea of parallax through the classic method of holding a single finger out in front of their face and closing one eye and then the other. Students see that the difference in the position of the finger when viewed from each eye, as viewed against the background of the classroom, is larger when their finger is closer to their face. Students thus get a qualitative feel for how the angle of parallax depends on the distance between the baseline (distance between their eyes) and the object whose distance is to be measured (their finger). Indeed, there are quantitative methods that can be employed in the science laboratory that involve making measurements of the distance between the eyes or viewing objects from different ends of a known baseline against a measurement scale drawn on the chalkboard. For example, in previous years, one teacher explained that students had performed a quantitative version of this activity using a protractor and pencil. Students had lined the pencil up with the object they were viewing and then recorded the angle it had made on the protractor. They then moved the protractor along the baseline provided by a meter ruler and remeasured the angle.

The trouble with these sorts of activities is that it is hard to point out what they should *actually* be seeing. The *expected view* can be explained verbally, but students may not actually see what the teacher wishes them to see. Thus, a smartphone camera gives them a pair of images that all can see and which can be measured.

To introduce the experiment, the astronomical method of parallax determination is explained and the parallels drawn with what they will do. That is to say, instead of using their eyes, astronomers use the changing position of the Earth itself as it travels about the Sun, a distance of some hundreds of millions of kilometers rather than a few centimetres. In addition, instead of using their finger, astronomers use a *nearby* star, some light years away, viewed against the fainter, and *assumed* to be further, background of stars. They will later learn that the nearest star (Proxima Centauri) is so far away that its parallax angle is a tiny fraction of a degree.

2.3. Calibration of the Camera

The first thing that the students do is calibrate their measurement device so that they can measure the parallax angle in degrees. Each smartphone will have a different field of view and a different image size. The field of view is first determined by placing the camera perpendicular to the base of a protractor; a pencil (or other thin object) is moved along the curved edge of the protractor until it can only just be seen at the edge of the screen (see Figure 1). The angles at the two extremes are noted, and the total angle yields a measurement of the field of view of the camera in degrees. The error in this measurement will be relatively large and of the order of +/− 2°. They then measure as accurately as possible the linear width of the screen of the smartphone with a ruler. The error will be of the order of +/− 1 mm.

The angle they have measured using the pencil and the protractor can then be divided by the linear dimension of an image displayed on the smartphone screen to yield a figure, whose units are degrees per centimeter or similar. They have thus measured the *plate scale* in degrees per centimeter. (Historical note: The term "plate" is from when astronomical imaging was undertaken with photographic "glass plates." We still use the term plate to refer to the image even though now we generally work with CCD cameras and digital photographs.)

Once students have measured the field of view of their smartphone, they can then use the following diagram printed out on a sheet of paper as their Earth–Sun system (see Figure 2). The two Earths represent the position of the Earth six months apart from each other. The distance between the two Earths should be 10 cm. Students can use the radial lines to make sure that their smartphone is pointing in a perpendicular direction to the Earth–Sun–Earth baseline.

At a distance of approximately 0.5 m directly in front of the mini-Earth–Sun system, a star symbol, such as that shown in Figure 3, is placed. It could be taped to a pencil and held in position on the bench, or floor, using some modelling clay or a clamp stand. Students should measure the distance from the baseline to the position of the star as accurately as possible using a meter stick. This is so that later students can estimate the error in their observations.

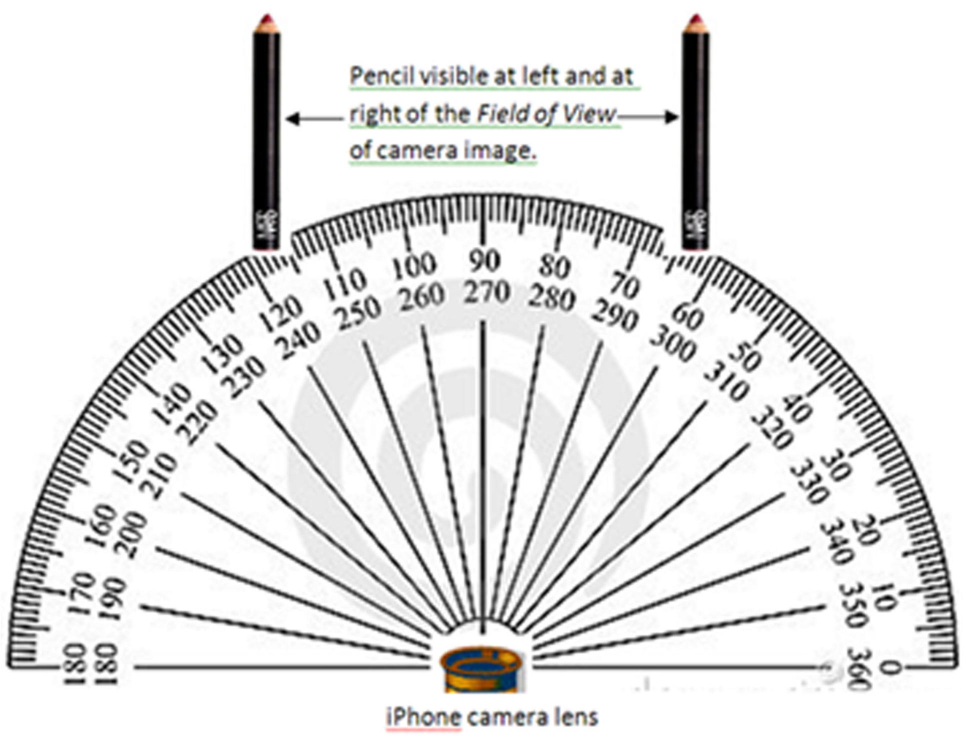

Figure 1. Method to find the field of view of the camera image.

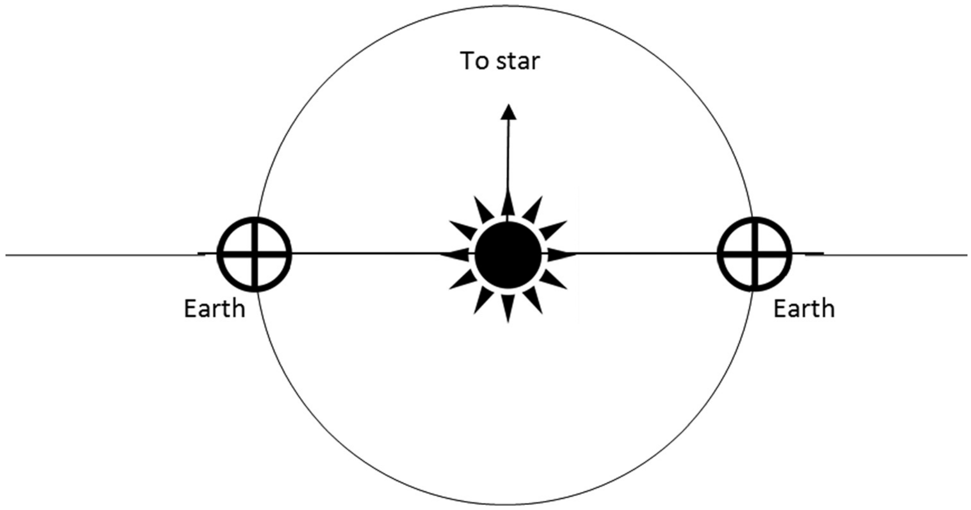

Figure 2. The mini Earth–Sun system.

Each photograph should be taken by positioning the camera at the extremes of the mini-Earth's orbit around the Sun. Care should be taken to center the camera lens on the cross of the mini-Earth before taking each photograph. Students may be able to position the camera with an error approximating +/− 2 mm. The results from using the first author's smartphone are shown in Figure 4.

From these two images, the parallax angle can be measured using the measured field of view of the camera and the linear approximation of the "plate scale" from the image size. Now, the student measures the distance in centimeters and millimeters on the smartphone screen between the "stars" in the two images, and using the *plate scale*, the parallax angle in degrees can be calculated.

A simple way to do this is to measure the distance from an object in the background to the point of the star in one image and then repeat this measurement with the other image. In the above photographs, the left hand side of the door in the background provides a convenient line from which to measure the change in position. The difference in the two positions can then easily be measured to an accuracy of +/− 1 mm.

Using a calculator, students then divide this distance by the plate scale to produce the angle through which the star appears to have moved in the two images. Halving this angle yields the *angle of parallax*, i.e., the angle subtended by the *radius of the Earth's orbit* at the distance of the star.

2.4. In Practice

In this example, the field of view is approximately 50° with a full screen width of 7.5 cm. The plate scale is thus 50°/7.5 cm or 6.7° cm^{-1} +/− 0.4° cm^{-1}. The error in the plate scale can be investigated by the students using a spreadsheet. They simply divide the maximum and minimum fields of view by the maximum and minimum linear size of the screen to arrive at a figure of +/− 0.4° cm^{-1}.

Figure 3. Star symbol.

Figure 4. Sample results from an iPhone 3GS.

The distance between the stars in the two images shown in Figure 4 above is 1.7 cm +/− 0.1 cm. This leads to the value of the parallax angle of 11.3/2° or 5.7° +/− 0.5° (or ((17 mm/75 mm)*50°)/2 (Note: the division by 2 is important given the definition of the *parsec*). Thus, using standard trigonometry

$$d = r/(\tan\theta),$$

where r is the *radius* of Earth's orbit (in this case 0.05 m) and θ is *half* the angle measured (in this case 5.7°).

The distance to the star, d, can thus be calculated. In this case, the result was 0.5009 m, which is very close to the 0.50 m initially measured from the baseline of the mini-Earth's orbit to the model star using the meter ruler. Measurement error in the distance to the star using the meter ruler would be approximately +/− 1 mm. The error in the smartphone method comes primarily from the distance measured on the screen, 0.017 m +/− 0.001 m. This leads to an error in the parallax angle of +/− 0.7° and leads to an error in the distance of +/− 0.03 m. In conclusion, the results of the experiment are acceptably accurate.

Now that the students understand the fundamental mechanisms and measurement techniques of parallax, they can be extended by comparing the scale of their measurements to the scale of the measurements used by astronomers. By using simple scaling mathematics, students can be asked two questions. The first is, "How far would you have to move the model star until the parallax angle is 1 arc sec?" They will find this to be approximately 10.26 km. There are 60 arc min in 1° and 60 arc sec in 1 arc min. Thus, to achieve a parallax angle of 1 arc sec, the star will have to be moved $5.7 \times 60 \times 60$ times further away.

Extending this, the second question is, "How far would you have to move the model star away to maintain this 1 arc sec parallax angle if you used the true radius of the orbit of the Earth rather than the 5 cm?" Thus, the paper star will have to be moved $149.5 \times 10^6 \times 1000 \times 20$ times further away. (The 5 cm original baseline is 1/20 of a meter.) The alternative question is, "How many times does 5 cm go into 149.5×10^6 km?" Through simple scaling mathematics and unit transformations, students arrive at an estimate of the value of a parsec that is surprisingly accurate. In this case, the answer to the last question is 3.068×10^{13} km compared with the value given by Wikipedia of 3.086×10^{13} km.

2.5. Extension: The Parallactic Ellipse

As mentioned in the introduction, there seems to be a common alternative conception about parallax where all nearby stars move linearly back and forth against background stars over the course of a year. This is only true, however, when a star is sitting in the ecliptic plane. The method just described is an example of this. The possible reason for this common alternative conception, and the format of the method we use above, is that it makes the conceptual description and mathematical manipulation quite easy. However, in doing so, it has omitted some vital concepts from the framework. All stars will trace out an *ellipse* on the sky, and the eccentricity of this ellipse is related to the nearby stars' ecliptic latitude. For a star on the ecliptic equator, the eccentricity will be 1 (i.e., a line); for a star at the ecliptic pole, the eccentricity will be 0 (a circle).

To explore this phenomenon, we can exploit the video (movie) function of the smartphone. Using a clamp stand to hold the star approximately 50 cm away from the smartphone, and by moving the inclined smartphone camera

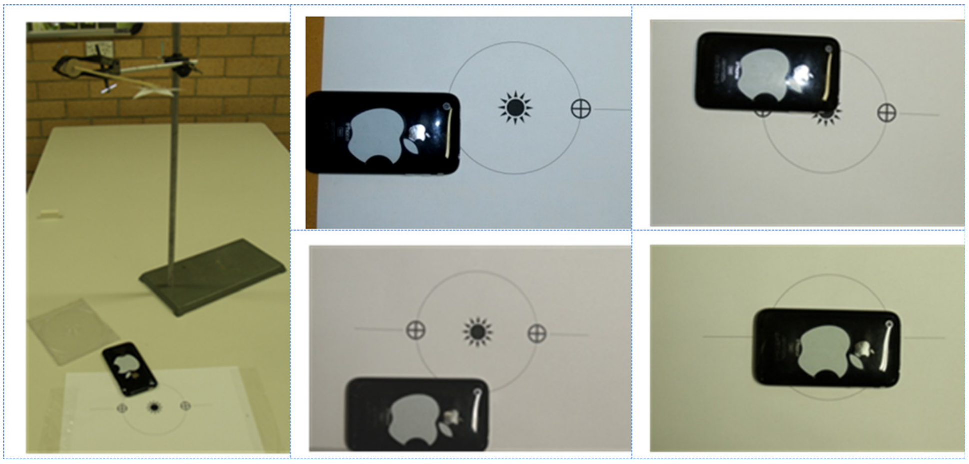

Figure 5. Clamp stand and moving camera setup for a star at the ecliptic pole.

sensor around the orbit of the Earth, we can create a movie of how a nearby star actually moves in the sky. Figure 5 shows the setup for the example of a star at the ecliptic pole, a video of which will show the star moving in a near circular path.

To examine the effects of varying the ecliptic latitude, the sheet of the Earth's orbit remains taped to the table and a CD case is used with a hole large enough to operate the touch screen of the smartphone cut in the top of the case. The setup is shown in Figure 6. Wooden or Lego^{TM} blocks can be used hold the top side of the CD case at an angle, and the camera can be affixed using some sticky tape. A mark can be made on the base of the CD case that is directly underneath the camera sensor. This mark is then made to move around the orbit of the Earth when the video is being recorded.

Since students are not actually *measuring* anything here, they do not need to know the exact angle at which the camera is sitting with respect to the surface. By making a series of videos from the ecliptic equator to the ecliptic pole (three or four), the students should find that the eccentricity of the parallactic ellipse decreases from the equator to the pole, as shown in Figure 6. If desired, measurements can be made of the eccentricity of the ellipse and related to the angle of the CD case that corresponds with ecliptic latitude. If this is done, then they can be led to discover that the eccentricity of the parallactic ellipse equates to the cosine of the ecliptic latitude.

3. EDUCATIONAL TRIAL

Students in Grade 11 at two local high schools tried this approach during their physics classes in June 2011. Students grasped the method rapidly and were able to start work quickly. In taking the photographs, the students realised that they had to have a background object so they could see their "star" "move." This opened a discussion about how far away was "far enough" in order to show movement but still have the background

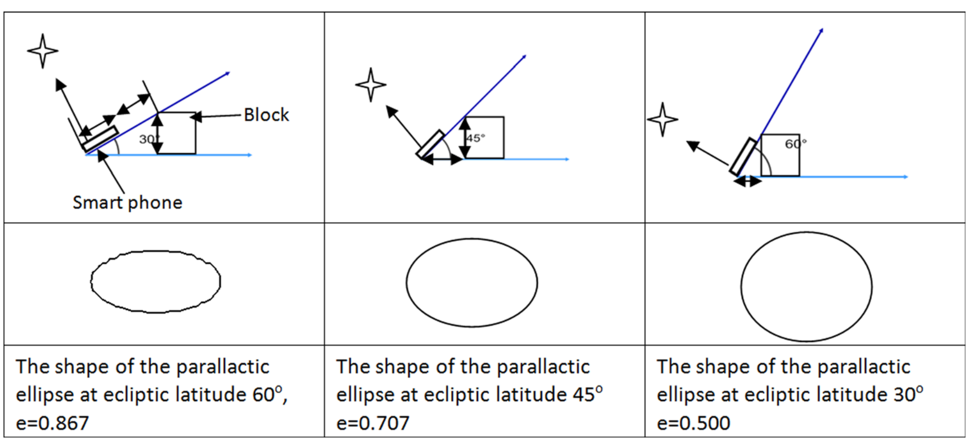

Figure 6. Example of the CD case setup and the shape of the parallactic ellipse at three ecliptic latitudes.

stationary. One group of students concluded that a larger distance would have been beneficial as it would be more “spectacular” as well as allowing a look at the error issues raised in the Section 2 in more detail.

So that they could compare the outcomes of their calculations, the actual distance to their object was measured using a ruler. Most students were able to get reasonable (<2%) accuracies. In one case, their teacher mentioned that, in previous years when students had conducted the experiment using the metre ruler and protractor referred to above, any answer within 10% was regarded as “very good.” One group of students, who are very competitive, got an answer to within 1% of the known value. This led to a discussion about why there was discrepancy in their measurements, i.e., what could have caused them.

Calculating the plate scale to get their measurements in degrees/centimeters took the greatest amount of time. It took a few attempts for some of the students to understand what these ratios meant: They had to stop and think about the content representations, e.g., the scale of model cars. The students did not tend to carry the mathematical tools from their mathematics classes into the science context with ease. Once the link was made, however, it became clear to them. The final step was to extrapolate to the stars. Throughout the activity, stellar observations were linked to their investigation in order to make the connection. In the end, all students successfully worked through an example of stellar parallax taken from a past examination paper.

3.1. Reflective Comments

The reactions of the teachers who tried this approach can be encapsulated quite simply. One summed it up as “I have *never* (emphasis) seen them so engaged so deeply for such a period of time” (SW). A second teacher described his students’ reactions thusly: “They were deeply engrossed and amazed at their results. They got a shock at how accurate they were” (DHJ). We presume that the second “they” in this last sentence refers to the results, though it could refer to themselves.

Students’ reactions were elicited using three open-ended questions. These were:

1. What things did you really like about the smartphone Parallax experiment?
2. What things did you *not* really like about the smartphone Parallax experiment?
3. What things would you change about the smartphone Parallax experiment to make it more fun and/or to be able to learn better?

Three categories of response were identified in relation to the first question. An enjoyment aspect was aptly summed up by one student’s comment that “It was superfun time! Different to other experiments.” A second category of response was given by the majority of students who commented on various aspects regarding the application of the method to astronomy, e.g., “[T]hat we could calculate basic parallax on Earth, that the same type of method is used to calculate distances of stars.” The third category of response related to particular scientific aspects, such as the accuracy or calibrations that were embedded within the investigation, e.g., “We could find out the field of view of our camera.”

In responding to what they did not like about the investigation, analysis of students’ comments revealed four broad categories: the effort involved, a lack of the technology, treatment of errors, and the scale of the experiment. The category of *effort* included comments about ensuring that their smartphone was always aligned correctly, e.g., “It was fiddly because the camera was not central.” Students seemed to get distracted by the need to ensure that their method was correct. This is interesting to note because it is on their effort to get the method just right on every occasion that scientists spend a lot of their time. This is an issue that will be addressed in future developments of the investigation.

A second category of negative comment related to the fact that some did not have a smartphone, e.g., “The school should supply us all with [smartphones].” A third category mentioned by only a few students related to the scale of the investigation, e.g., “The scale of the desk is not really impressive.” These students were not impressed by the fact that they had measured the distance to a paper star on their workbench. For them, that was not “spectacular enough.”

The final category of response related to the calculation of errors. Five responses were listed in this category. These comments could be regarded as very useful given that nowadays science courses at the high school level in this state (New South Wales) seldom pay much attention to the concept of error. At least one could conclude that in making comments about error and accuracy, the students had become aware of the need to pay detailed attention to the method and had arrived at, the very least, a qualitative if not quantitative understanding of error and error treatment, e.g., "I didn't like that our error margin was greater than 30%."

4. CONCLUSION

In this paper, we have provided an overview of a practical activity that can be performed within a reasonable timeframe with familiar equipment for students to understand deeply the concepts underlying parallax and the parsec based on a hands-on investigation. We have noted, albeit not-conclusively, that there appears to be some alternative conceptions regarding the ideas behind parallax in general. We have also presented the reactions of teachers and students with whom the approach has been field-tested.

The next step for students to take is to extend their experience with the concept of parallax using this methodology to measure the parallactic ellipse of an actual star, and from that, determining its distance. They will be exposed to the measurement techniques used by astronomers to measure very small angles. To this end, we have been collecting high quality CCD images of the nearest star to our solar system over the past eleven months: Proxima Centauri.

The stellar parallax materials are currently being developed for use in the Australia Research Council funded project *Space to Grow: The Faulkes Telescopes and improving science engagement in schools*, a collaboration between Las Cumbres Global Telescope Network, Macquarie University, and Charles Sturt University. The materials are in the process of being field tested with students and teachers in collaborating schools in the Catholic Education Dioceses of Parramatta and Bathurst and the Department of Education and Communities in Western Region New South Wales, Australia.

Acknowledgments

We wish to thank the students and teachers in the various educational jurisdictions who have participated in the ARC Linkage Grant Space to Grow. Their insightful contributions, both pragmatic and professional, have been outstanding. We also wish to thank the Australia Research Council for their support in providing the grant and to the Catholic Schools Offices in Bathurst and Parramatta and the Department of Education and Communities Western Region, NSW for their participation. Finally, we also wish to thank the anonymous referees for a number of helpful suggestions to improve the quality of this paper.

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