PAPER

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Peeping over Galileo's shoulders: laying the foundations of heliocentrism in elementary school

M M Pincelli[1], M Brustle[2], M del C Formichella[2], C Perez-Millán[3], N Palmieri[2] and S Otranto[1]

[1] Departamento de Física, Instituto de Física del Sur (IFISUR), Universidad Nacional del Sur (UNS), CONICET, Av. Alem 1253 B8000CP, Bahía Blanca, Argentina
[2] Colegio Victoria Ocampo, Brown 236, B8000LQF Bahía Blanca, Argentina
[3] Departamento de Física, Universidad Nacional del Sur, Av. Alem 1253 B8000CP, Bahía Blanca, Argentina

E-mail: michelina.pincelli@uns.edu.ar

Abstract

In this work, an adaptation is developed of the first observation attempted by Galileo to demonstrate the heliocentric hypothesis to be correct. The objective is to enable students in their final year of elementary school to confront by themselves the same contradictory evidence that Galileo confronted during the second decade of the 17th century. The results of its implementation in two classes of 32 students aged 11–12 years are reported, and the first impressions of this pedagogical approach are analyzed.

1. Introduction

The development of children's critical thinking during their primary school years is one of the most important challenges that educators must face, as new generations enter the early stages of their instruction while immersed in an unprecedented technological environment. The role of the teacher, who used to be mostly in charge of the transmission of topical knowledge, is slowly transforming into one which concentrates on the development and optimization of students' capacity to steer their own learning process, taking for granted their independent access to large sources of information of variable reliability [1–3]. The natural sciences provide the ideal context in which to pursue this objective, as our present knowledge of nature stems from a highly refined, self-correcting system that has been optimized over the past 400 years [2]. In contrast, and despite the fact that the advantages of the scientific procedure and the benefits of critical thinking are proclaimed in many elementary schools' curricula and classroom textbooks, more often than not, students are obliged to memorize facts and dates imparted in oversimplified presentations. As a result, the winding roads that humanity had to follow to reach the current state of knowledge, as well as the time taken to do so, go unnoticed.

Among other topics, the transition from the geocentric theory to the heliocentric clearly reflects these statements and is the focus of the present work. A survey of the educational resources recommended by the Regulatory Education Boards in Argentina to introduce the solar system revealed

detailed descriptions, with planets ordered in terms of their proximity to the sun, their relative sizes, composition, etc. The idea of a transition from a geocentric to a heliocentric vision of the universe has been also detected in some textbooks, specially referring to science as a social construction. Graphical representations of the models of Ptolemy and Copernicus are invoked in this case, and suggest that the latter was proved to be correct thanks to the introduction of mathematical models and the invention of the telescope by Galileo. Students are led to think that an incorrect model was considered valid for at least 1300 years, at which point the correct model was introduced, which can hardly bridge the underlying conceptual gap. After all, their daily experience tells students that the sun rises and sets. The way in which humanity, with an Earth-based perception of the universe, concluded that the heliocentric conception was the correct one, and how long it took to demonstrate, and whether it was an easy or difficult task, are some of the questions that are beyond the reach of many students and teachers alike. Interestingly, it is within those questions that the richness of the topic lies, and where the gymnastics of the critical thinking procedure can be practised.

In this work we propose and implement a sequence of activities that revisits Galileo's first attempts to detect annual parallax, in 1617, when he focused his telescopic observations on Mizar A and B in the Big Dipper in the constellation of Ursa Major. The study encompasses 32 students in their final year of elementary school at Colegio Victoria Ocampo in Bahía Blanca, Argentina. Firstly, we focus on the pillars of Galileo's model and measure the angular size of an object at various distances by means of a calliper of our own design, built with a wooden rod and cardboard jaws. Its scale is graduated in degrees and permits the direct measurement of fractions of a degree. We then perform a scale model of the Earth's orbit, and Mizar A and B, from which students can gain an insight of the expectations that Galileo had with respect to the change of the relative position of these two stars throughout the year. These observations are contrasted to those obtained with Stellarium[4] software. Exactly as

happened to Galileo, Stellarium does not lead to a noticeable visual effect and places students at a crossroads. At this point, they are asked to revisit and analyze the reliability of all the elements conforming to Galileo's model.

The activities are conceived in such a way as to use the students' mathematical knowledge of angles and geometry, allowing in this sense an interdisciplinary approach to the topic. In the same spirit, we have recently presented pedagogical sequences to determine the retrograde motions of Mars as seen from the Earth [4], and to tackle the pioneering experiment of the Comte de Buffon to estimate the age of the Earth [5]. These activities stem from a new design of the natural sciences curricula for elementary schools, which is being developed in a joint collaboration between scientists of the Physics and Chemistry Departments at the Universidad Nacional del Sur and the staff of educators at Colegio Victoria Ocampo in Bahía Blanca, Argentina. This initiative has been endorsed by the Regulatory Education Board of the Province of Buenos Aires, Argentina.

In the next section, we present the historical background; we describe Galileo's model and his expectations with regard to the observation of Mizar A and B. In section 3, we describe the proposed sequence of activities and the way in which they were implemented. In section 4, conclusions are drawn.

2. The heliocentric theory and Galileo's model

By 1514, the *Commentariolus* published by Nicholas Copernicus was spreading among academic circles throughout Europe. In this publication, Copernicus shifted the Earth from the center of the Universe and proposed a heliocentric model in which he sought to resolve many of the weaknesses of the Ptolemaic system. Two complementary publications, *Narratio prima* (1540) and *De revolutionibus orbium coelestium* (1543) provided a complete description of this system. In a Europe convulsed by religious and political tensions, this theory immediately found supporters and detractors. One experiment would prove heliocentrism to be correct: a detectable change of distance between two stars throughout the year. This should be a consequence of the change of visual perspective of the stellar background from

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[4] Free software available for different operating systems and widely used by amateur astronomers worldwide: www. stellarium.org.

a moving Earth. This effect is known, and will hereafter be referred to, as stellar parallax.

In 1597, Galileo Galilei corresponded with Johannes Kepler, recognizing that he had been a Copernican for many years. In his reply, Kepler suggested that Galileo study the visual angle between the Pole Star and the first star of the tail of the Little Bear, to search for the stellar parallax. Kepler estimated that a quadrant with an angular resolution of 15 arcseconds was needed; an instrument that he did not have at Graz [6]. It is worth noting that Copernicus' instruments had a resolution of about 0.125° (7.5 arcminutes), while the large instruments designed and constructed by Tycho Brahe were able to resolve up to 1 arcminute by eyesight [7]. Improving angular resolution towards the arcseconds range was probably a most difficult technological challenge in those days. As more precise instruments were built, the fact that the detection of stellar parallax remained elusive implied that the universe was much bigger than previously thought.

Thirteen years later, in 1610, Galileo developed and turned to the heavens a small refractor telescope that could detect faint stars, not visible to the naked eye, and measure angles much smaller than those previously recorded. In fact, it is now recognized that Galileo was then able to resolve the positions and apparent sizes of objects to an accuracy of about 2 arcseconds [8, 9]. In *Sidereus Nuncius*, published in the same year, Galileo showed his sketches of the telescopic measurements of the four satellites of Jupiter he could resolve, as well as the moon's structure and the constellation of Orion. Soon after, on 23 July 1611, Lodovico Ramponi wrote to him to suggest his telescope be used to detect stellar parallax. He suggested a method based on the observation of optical double stars, as shown in figure 1. These are stars that appear optically close to an observer on Earth but which are actually unrelated and could be far apart. In Ramponi's sketch, this would be the case with stars A and C or B and C. The visual perception of a change of perspective of a star (C) located closer to the sun with respect to a distant star (A or B in this case) as the Earth moved from position 1 to position 2, would be sufficient evidence to prove heliocentrism to be correct.

It is worth noting from their correspondence that the concept of a sphere of fixed stars, inherited
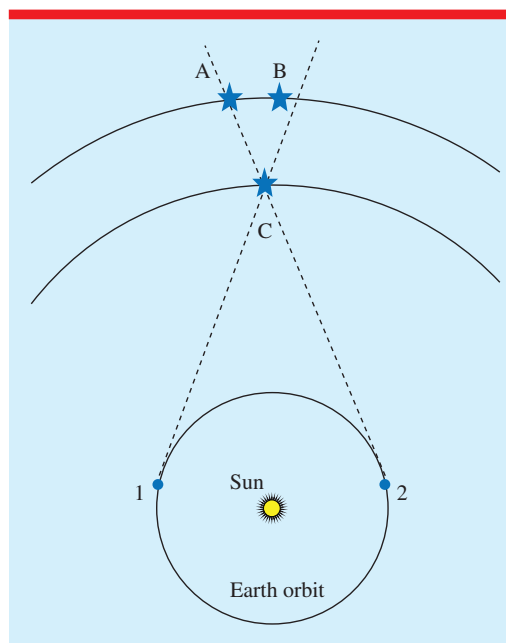

Figure 1. Replica of Ramponi's sketch in his letter of 23 July 1611 to Galileo, to explain his method of using optical double stars to measure annual stellar parallax with a telescope. Letters indicating the Earth's position have been changed to numbers for easier understanding.

from the Greeks and still held by Copernicus, was being gradually replaced by the picture of a universe in which stars were at varying distances from the sun, as first proposed by Thomas Digges in 1576.

A few years later, in 1617, Galileo used the double star method to try to detect the stellar parallax of Mizar A and B in the Big Dipper in the constellation of Ursa Major. The pillars of his model are detailed in the following. In concordance with Ramponi's suggestion, Galileo considered these two stars because they were optically close. (He measured a separation of only 15 arcseconds between their centers.) Moreover, he assumed that all stars were identical to the sun, and that their different brightnesses and apparent sizes were because they were located at different distances from the sun. He then used this context to determine how far those stars are from the Earth. We detail that procedure. By making use of the small angle relation for tan α, the angle α subtended by a star is given by D/r, with D being the diameter of the star and r its distance from the Earth. The angular size α subtended by a star at a
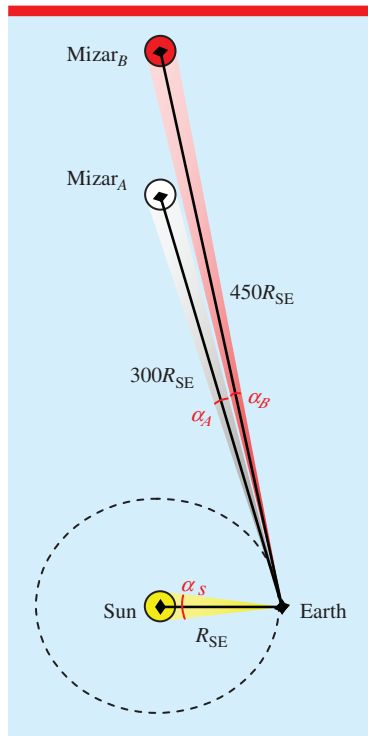
Figure 2. Graphical representation (not to scale) of Galileo's model for the system composed by the sun, the Earth, and Mizar A and B. His measurements of the angles subtended by the sun, Mizar A and B (α_S, α_A and α_B) led him to estimate the distance between Mizar A and the Earth as being 300 times greater than R_{SE} (the distance between the sun and the Earth) and the distance from Mizar B to the Earth as 450 times R_{SE}.

distance r is then related to the apparent angular size α' subtended by another star at a distance r', by the following relationship:

$$\frac{\alpha}{\alpha'} = \frac{r'}{r}. \tag{1}$$

Based on the apparent angular sizes of Mizar A and B, which Galileo directly measured as being 6 arcseconds and 4 arcseconds respectively, and by taking into account that the sun subtends an angle of 30 arcminutes at a distance R_{SE} from the Earth, the geometric relation equation (1) indicated that Mizar A had to be at a distance of 300 times R_{SE}, while the corresponding distance to Mizar B had to be 450 times R_{SE}. Such a geometrical configuration, shown in figure 2, provided rather favorable circumstances for the visual detection of annual parallax, and the

settling of the heliocentrism–geocentrism dispute. In fact, had this model been correct, Mizar A and B would have swung around each other in the sight of the eyepiece if observed over a period of months. Observations proved that this was not the case. Galileo was unaware that he was not really observing the diameters of the stars, but diffraction patterns. Mizar A and B are much further from the sun than his estimates. It would take another century for the diffraction effect to be identified and understood.

Despite having tried unsuccessfully to measure stellar parallax for nearly two decades, in 1632 Galileo published his *Dialogue concerning the two chief world systems*, in which, via the character Salviati, he explained his views and set out how stellar parallax should be explored in the future.

Many efforts would be needed over the next two centuries by other prominent scientists, among whom we can cite Robert Hooke, James Bradley, William Herschel, and Friedrich Bessel, who finally succeeded in measuring the stellar parallax for 61 Cygni in 1837 [10], almost 300 years after Copernicus' time.

3. In the footsteps of Galileo

In the days before the implementation of these activities, the elementary school students solved a series of mathematical problems and exercises driven to reinforce the arc-length concept; specifically, the idea that for a given angle, the arc-length of a circle increases with the radius. By the time the present sequence was implemented, the students were already familiar with the concept of angles and were proficient in the use of school protractors with a 1° resolution. By determining how the size in millimeters of an arc-length corresponded to 1° increases for increasing radii, the possibility of dealing with fractions of a degree was already established.

The implementation of the proposed sequence took four hours (two hours a day, on two consecutive days). Firstly, a presentation was made to introduce the students to the dilemma that faced scientists in the early 16th century regarding their models of the universe. Resembling the 'spot the differences' game, two figures representing the heliocentric and the geocentric models were presented to the class, with no specific legends. The
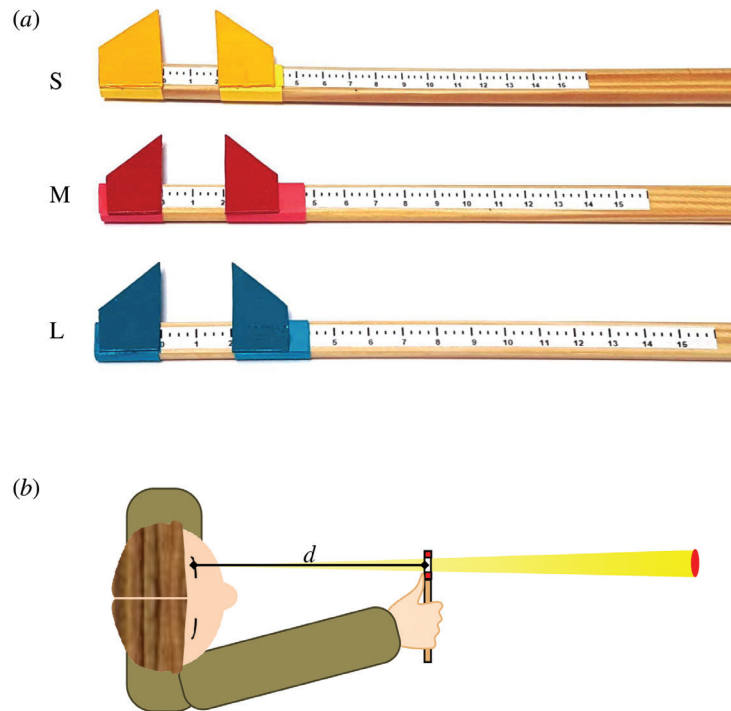
(*a*)

(*b*)

Figure 3. (a) Wooden rod callipers of sizes S, M, and L used to measure the angle subtended by a distant disc. The scale is in degrees, with a resolution of 15 arcminutes, and is dependent on arm length (see text for details). (b) Measurement procedure: the angle subtended by an object is measured with the calliper located at a distance *d* from the eye.

Table 1. Calliper scale design. The length (in mm) associated to an angle of 1° is indicated for three sizes corresponding to different ranges for the eye-to-calliper distance *d*.

Size	*d* (cm)	1° size (mm)
S	40–52	8
M	52–63	10
L	63–75	12

students immediately identified both representations, using the terms 'heliocentric' and 'geocentric' in their arguments. Moreover, most of them indicated the heliocentric system as the valid one, even though the matter of validity was not mentioned by the educators in charge. However, when they were asked to provide supporting evidence for their choice of the 'valid' model, they were unable to do so. Some argued that 'science says so,' but when they were asked 'how does science say so?' they could not explain. The question took them by surprise. At that point we invited them to join us in the adventure of learning 'how we came to know' that the Earth orbits around the sun. To

Figure 4. Measurement of the angle subtended by a 32 cm diameter cardboard disc at a distance of 6 m.

our pleasure, the invitation was welcomed by the group.

Our first objective was to give students a deep understanding of the basic components of Galileo's model, as follows.
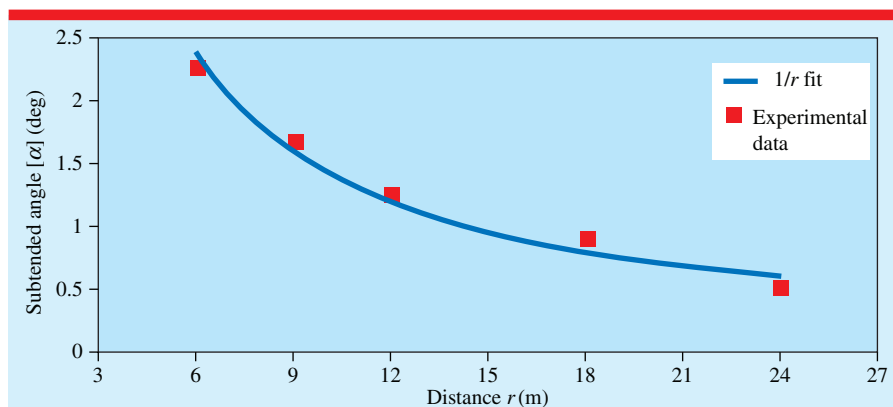
Figure 5. Mean values for the students' measurements of the angle subtended by a 32 cm diameter disc as a function of the distance *r* from the observer.

1. Stars are not placed in a sphere of fixed radius.
2. All stars are identical to the sun.
3. Bigger, brighter stars are closer to us than smaller, fainter stars.
4. Stars' distances from the Earth can be estimated by measuring their subtended angles.
5. As the Earth moves in its orbit, the change of perspective should be reflected in the observed star patterns.

While the first three points are acceptable for students, at least at the beginning, the fourth point implies a procedure with which they are unfamiliar. Since we could not deal in trigonometric relations with our audience, and as even equation (1) was out of scope, many of the proposals that can be found in the literature for secondary schools were ruled out [11]. In consequence, our first activity was designed to make the students understand the underlying concept.

Hence, we proposed the direct measurement of the angle subtended by a 32 cm diameter disc at different distances (6 m, 9 m, 12 m, 18 m and 24 m). For this purpose, we designed a calliper consisting of a wooden rod with cardboard jaws, as shown in figure 3(a)). Since the angle measurements are performed in terms of the arc-length subtended by an object, the size corresponding to 1° is clearly dependent on arm length. For our purposes, we classified the students according to their eye-to-calliper distance *d* (see figure 3(b)) in three sizes (S, M, and L) as indicated in table 1. The linear scale provides a direct reading of degrees and is generated by means of the small

angle relation $\alpha = D/r$. Therefore, we restricted its use to angles of less than 10°. A clear advantage of using such a simple device is that it can directly measure fractions of a degree. In our case we used a separation of quarters of one degree, but it is worth noting that one more subdivision, to eighths of one degree, would have provided the same resolution as that used by Copernicus in the first half of the 16th century. A photograph taken during the measurement process is shown in figure 4.

That brought to an end the activities on the first day. After school that day, the authors analyzed the individual records and calculated the average value of the angle α obtained by the students as a function of the distance *r*. The results are shown in figure 5.

The r^{-1} dependence is clearly devised, and allows discussion of the fact that beyond a certain distance, their instrument cannot resolve tiny differences in angular terms. In other words, the angular resolution of their instrument is a limitation on the maximum distance that can be measured.

At the beginning of the second day we showed them this figure, and together discussed the results obtained the previous day. We also showed them the old painting of Tycho Brahe with his huge mural quadrant [12] and allowed them to work out by themselves the reason for those big instruments, and to determine, after a close inspection of the painting, the different marks used in the scale and how they relate to degrees and fractions of degrees.
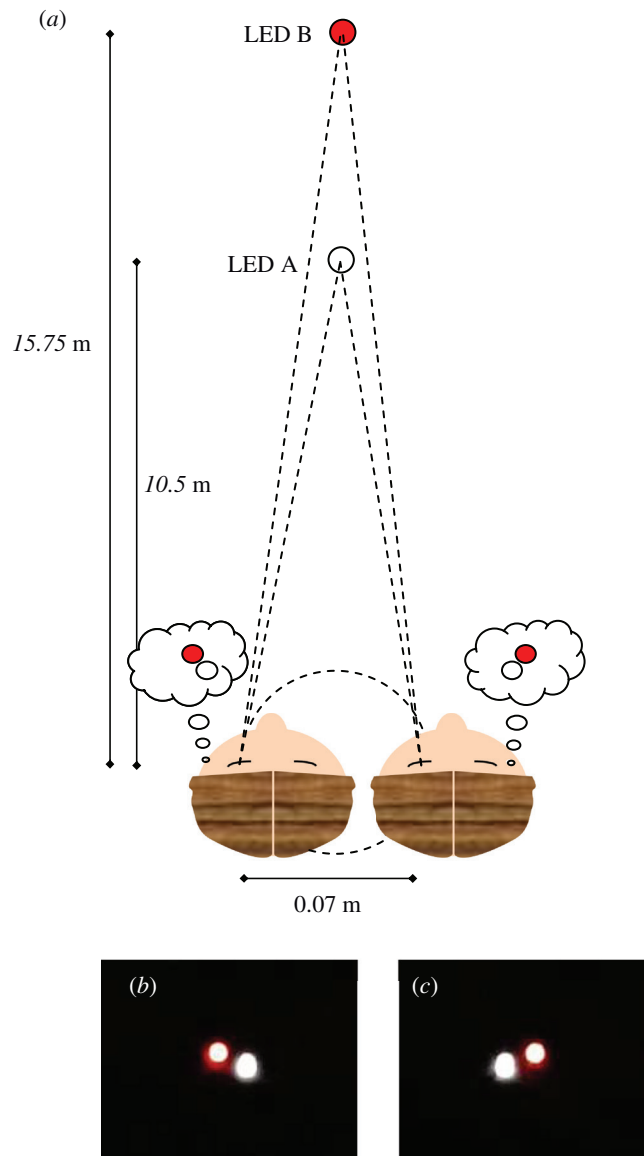
Figure 6. (Top) (a) Setup used to observe the translocation of the images of LEDs A and B. (Bottom) Photographs taken from the observation posts on the left (b) and on the right (c).

At this point, we tackled the fifth and last point of Galileo's model. This is familiar to many children but is nonetheless a nontrivial point. Many teachers and parents have heard remarks such as 'the moon is following me' from children in kindergarten or the early years of elementary school. Such a comment is more likely to be made during a car journey. These phrases provide a clear indication of how a child's brain struggles to deal with the change of perspective when looking at a nearby moving object set against a 'static' distant background.

Hence, to deal with this fifth point and to experience Galileo's expectations regarding his observations of Mizar A and B in 1617, we performed a scale model of the astronomical context derived from his estimations. To do so, we used two LED lights to represent Mizar A and Mizar B, and set two 'observation posts', separated by the diameter of the orbit of the Earth around the

Figure 7. Stellarium representation of Mizar A and B as seen from Florence, Italy (a) on 1 January 1617 at 6:00hs and (b) on 1 May 1617 22:04hs. Insets show Mizar A and B with a magnification of 560×. The dates are figurative and have been arbitrarily chosen.

sun, as shown in figure 6(a). These posts represent a six-month time lapse between observations, providing the most favorable geometrical arrangement to detect the stellar parallax. Due to the spatial limitations of the classroom, the LEDs were set at distances of 10.5 m and 15.75 m from the 7 cm segment running between the two observation posts. To help students distinguish both lights, white (Mizar A) and red (Mizar B) LEDs were used, and the room was partially darkened. The photographs shown in figures 6(b) and (c) were taken from the observation posts. Students were asked to sketch their observations.

At this point, we made use of Stellarium software and checked for visual differences of the relative positions of Mizar A and B over several months in Florence, Italy, where Galileo performed his observations. Beforehand, special care was taken by the educators in charge to search for observation times at which the Ursa Major constellation shows the same orientation to the Earth-based observer. We consider this an essential step, considering the students' ages, since it rules out any possibility of misinterpreting the observations as being orientation-related. For an observer in Florence, Ursa Major is a circumpolar

constellation. This means that it can be seen during the whole year, but due to the Earth's rotation, it rotates around the North Pole in a 24-hour cycle. Since the constellation shows a given orientation at earlier times as months go by, we proposed to start the observations at dusk. As months passed, the same orientation will be achieved at earlier hours during the night. Although a six-month lapse would maximize the expected parallax effect, it is clearly not feasible, since observations are limited by daylight. Hence, we decided to shorten the lapse between observations to four months, which according to our previous experience with the LEDs would still provide a valid context for our purposes. The results obtained from the simulator are shown in figure 7 and do not exhibit the trends predicted by Galileo's model. This contradiction placed students at a crossroads, as it had done with Galileo, 500 years ago. The question 'what do the Stellarium observations mean?' triggered a wonderful debate. To the teachers' delight, one of the students, who had argued on the previous day that it was the Earth that moved, telling us that 'science says so,' now stated 'the Earth is still.' To overcome this instance, we revisited together the basic elements of Galileo's model and analyzed their reliability. While point 1 of Galileo's model still looked reasonable to them, points 2 and 3 were quickly challenged by some, who realized that if stars were not identical to the sun, as considered by Galileo, the real distance to Mizar A and B would be unknown and all our expectations would then fall to pieces.

Finally, as a closure activity, a historical tour was presented to the students regarding the post-Galileo era, up to the measurement of the parallax of 61 Cygni by Bessel in 1837.

4. Conclusions

In this work we designed and implemented a pedagogical sequence at the upper elementary school level, aiming to understand the difficulties that had to be faced before the heliocentric theory was proved to be correct.

Rather than giving a factual exposition of the solar system, or the dilemma of the 'correct' model versus the 'incorrect' model to which an oversimplified presentation might lead, the present sequence highlights a context that puzzled humanity during a period of history in which science was flourishing. With an understanding of the characteristics of the model invoked, their predictions, and their contrast to the observable evidence, provided a unique scenario for critical thinking and would let students assimilate why it took approximately 300 years to settle this problem, after great efforts by many renowned scientists.

The preliminary results of this implementation, with a set of 32 students in their final year of elementary school, are encouraging. During its development, the students engaged easily and took active roles in the activities and discussions. Some of them sought further information on the topic at home, which generated questions that were brought to the classroom in the following days. From the school perspective, it is also worth noting that some parents explicitly congratulated the teacher for the motivational urge these activities generated in their children. From a pedagogical point of view, we consider that it could be useful to have the students become used to handling the calliper at a prior stage. We noted that some students had to be assisted while reading the scales, especially when the readings were in between two marks.

For subsequent implementations, articulation with the pedagogical sequence previously introduced for the retrograde motion of Mars as seen from the Earth [4] is strongly recommended. This would provide a much stronger background to understanding what urged Copernicus to introduce his model, and why Galileo and many other scientists were so strongly committed to the Copernican theory.

Based on its strong interdisciplinary context, it is our hope that this set of activities will provide the students with long-lasting memories, and help strengthen their critical thinking skills for the future.

References

[1] Sagan C 1997 *The Demon-Haunted World, Science as a Candle in the Dark* (London: Headline)

[2] Chalmers A 2013 *What is this Thing Called Science?* (Brisbane: University of Queensland Press)

[3] Zohar A 2004 *Higher Order Thinking in Science Classrooms* (Berlin: Springer)

[4] Pincelli M M and Otranto S 2013 A hands-on exploration of the retrograde motion of Mars as seen from the Earth *Phys. Educ.* **48** 448–54

[5] Pincelli M M, Prat M R, Lescano G M, del C Formichella M, Brustle M and Otranto S 2018 The kickstart of the age of the Earth race: revisiting the experiment of the Comte de Buffon at school *Phys. Educ.* **53** 015015

[6] Siebert H 2005 The early search for stellar parallax: Galileo, Castelli and Ramponi *J. Hist. Astron.* **36** 251–71

[7] Chapman A 1983 The accuracy of angular measuring insttruments used in astronomy between 1500 and 1850 *J. Hist. Astron.* **14** 133–7

[8] Graney C M 2007 On the accuracy of Galileo's observations *Baltic Astron.* **16** 443–9

[9] Graney C M 2008 But still, it moves: tides, stellar parallax, and Galileo's commitment to the Copernican theory *Phys. Persp.* **10** 258–68

[10] Bessel F W 1838 On the parallax of 61 Cygni *Mon. Not. R. Astron. Soc.* **4** 152–61

[11] Pössel M 2017 Finding the scale of space *Sci. Sch.* **40** 40–5

[12] princeton.edu/~his291/Mural_Quadrant.html

Marina Brustle holds degrees of kindergarten and school teacher and has wide experience in the primary school level. She actually serves as the vice principal of Colegio Victoria Ocampo in Bahía Blanca, Argentina.
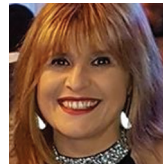
María del Carmen Formichella holds a degree as school teacher and a degree in education management. She has wide experience teaching in the primary school level. She actually serves as the principal of Colegio Victoria Ocampo in Bahía Blanca, Argentina.

Cecilia Perez-Millán holds a Masters degree in the Education of Natural and Exact Sciences. She holds a position as Head of teaching assistants at the Universidad Nacional del Sur. Her research interests are focused on Physics education at all levels.

Natalia Palmieri holds a degree as school teacher. She is actually teaching natural sciences and mathematics to 6th graders at Colegio Victoria Ocampo in Bahía Blanca, Argentina.

Michelina M. Pincelli has a PhD in physics from the Universidad Nacional de Córdoba, Argentina, where she joined the nuclear magnetic resonance group. She now holds a position as a professor of physics at the Universidad Nacional del Sur. Her actual research programme is focused on the development of strategies to improve science education at different educational levels.

Sebastian Otranto has a PhD in Physics from the Instituto Balseiro, Argentina. He is an associate professor of physics at the Universidad Nacional del Sur and a researcher for the National Research Council of Argentina (CONICET). His research is focused on the theoretical study of atomic and molecular collision processes and on science education topics.