

## ASTRONOMY EDUCATION PRACTICE

# Suggested classroom activities to promote perspective-taking in astronomy by projecting images from a phone or tablet up unto a screen

Pierre Chastenay<sup>1,\*</sup>

<sup>1</sup>Département de didactique, Université du Québec à Montréal, Case postale 8888, succursale Centre-ville, Montréal (Québec) H3C 3P8 Canada

\*[chastenay.pierre@uqam.ca](mailto:chastenay.pierre@uqam.ca)

## Abstract

Astronomy is a spatial science that requires connecting and comparing different points of view on astronomical systems to understand their complex mechanisms. Textbooks' illustrations often fail to provide such connections, whereas 3D models of astronomical systems that students can "manipulate" are more conducive to learning. But providing learners with different perspectives simultaneously on an astronomical model can be difficult. One way to achieve this goal is by using a smartphone's or tablet's camera to capture the geocentric point of view, and sending the image in real-time via a casting device on a TV monitor or projecting a video image on a screen for all students to see. This way, learners can easily switch from their own "space-based" (i.e., allocentric) perspective on the model to what an observer on Earth (i.e., the view captured by the camera) would see at the same time. In this Best practice paper, presented principally as a resource for educators, we review the relevant literature on teaching astronomy with concrete models and promote classroom activities that use cameras, casting devices and projectors to teach the diurnal cycle, the phases of the Moon and eclipses, the seasons, and planetary motion.

**Keywords:** Casting devices, Diurnal cycle, Eclipses, Phases of the moon, Planetary motion, Seasons, Smartphones and tablets, Spatial abilities

## 1 Introduction

Basic astronomical content, like the diurnal cycle of day and night, the phases of the Moon, lunar and solar eclipses, the seasons, and planetary motions in the solar system, are all regularly taught in schools at the elementary, middle and high school levels in most states and provinces in the United States and Canada (National Research Council, 2012, 2013; Council of Ministers

of Education, Canada, 1997), as well as in most OECD (Organization for Economic Co-operation and Development) member countries (Salimpour et al., 2020).

Martinez Pena & Gil Quilez (2001), Chastenay (2014; 2018) and Chastenay & Riopel (2019) have found that most teachers at these school levels turn to textbooks and the images and illustrations they contain to teach these highly complex astronomical topics. But astronomical images and illustrations found in text-

books are usually two-dimensional, not-to-scale, static, implicitly portrayed in perspective (but rarely explicitly described as such) and are overall extremely difficult for students to analyse and understand.

Lee (2010) noted that science textbooks images are increasingly considered by researchers as a likely source of confusion for students who, contrary to science experts, lack the basic conceptual knowledge to interpret them and correctly understand the information they convey. Some, like Stern & Roseman (2004), even consider many science textbooks illustrations as counter-productive to the learning of scientific ideas. In the specific case of astronomical systems portrayed in science textbooks, several authors (Åberg Bengtsson et al., 2017; Calderon-Canales et al., 2013; Kikas, 1998a,b; Michaels and Bruce, 1989) have found that astronomical illustrations are the source of the most common misconceptions found among students, like the Earth's shadow cast on the Moon to explain the lunar phases, or the variation of the Sun-Earth distance to account for the changing of seasons. Writing about the typical illustration for the mechanism of lunar phases found in most science textbooks, Trundle, Atwood & Christopher (2007a) remark: "We see no basis in our work or other literature for concluding that the typical study of moon phenomena in school, supported by text and two-dimensional drawings, contributes importantly to understanding Moon phenomena. In fact, we hypothesize that it does not." (p. 613)

When teachers use science textbooks to teach astronomy, they assume that the illustrations they contain convey information that students will use to build a mental model of the astronomical system represented. But, for one, there is usually not enough information in these images to allow the construction of a complete and effective mental model by students (Schnotz and Bannert, 2003). What's more, it is extremely difficult for them to match their natural, egocentric frame of reference on celestial events (i.e., the view from Earth, see Black, 2005; Nussbaum, 1985) with the view from space that is usually the norm in textbook illustrations of astronomical systems (i.e., the God's eye view). Given these difficulties, it is alarming that textbooks dominated by texts and illustrations as meaning-making mediums (Mathewson, 1999) are still so prevalent in astronomy teaching, while classroom activities that promote spatial skills, especially perspective-taking – so central to the understanding of astronomical concepts (Plummer et al., 2016) – are so seldom used to teach basic astronomical topics.

## 2 The “spatial” component of astronomy teaching

Astronomy is indeed a “spatial” science, not only because astronomical objects exist and move in three-dimensional space, but also because understanding basic astronomical topics like the diurnal cycle of day and night, phases of the Moon, eclipses, the Earth's seasons, or the apparent motion of planets across the sky, all require an ability to move from one frame of reference to another (Heywood et al., 2013; Plummer and Maynard, 2014; Subramaniam and Padalkar, 2009), specifically shifting between the view from the Earth's surface (i.e., the geocentric point of view) and the view from space (i.e., the “allocentric” point of view, see Chastenay, 2016). In fact, as Sadler (1992) pointed out, “without the ability to imagine what objects look like from different perspectives, students will find many astronomical concepts virtually impossible to learn.” (p. 103) Fortunately, spatial skills or spatial abilities, especially perspective-taking, can be learned, and should in fact be the subject of specific teaching, as their importance in various STEM domains (physics, architecture,

engineering, chemistry, etc.) has been frequently demonstrated (Newcombe, 2017). Astronomy teaching can certainly play a role in promoting spatial abilities among students; for example, since perspective-taking skills seem to predict a student's ability to explain astronomical phenomena, Plummer, Bower & Liben (2016) recommend that “science educators foster this type of reasoning and provide children who have low perspective-taking skills with additional spatial aids, such as simulations showing the Earth-based perspective and physical models to support explanations.” (p. 362)

Indeed, one way around science textbooks and the illustrations they contain is to model dynamic astronomical systems in the classroom, for instance by displaying concrete models of the Sun-Earth-Moon system to demonstrate diurnal cycle, phases of the Moon, eclipses and the seasons (Kavanagh et al., 2005; Sneider et al., 2011), or by building a human orrery with the help of students to demonstrate planetary motion (see Bailey et al., 2005; Newbury, 2010; Thompson, 2005).

In this paper, we will review the most common astronomical models used in the classroom to teach basic astronomical concepts, and we will propose a way to overcome one of their most important limitations, i.e., the fact that each student viewing the model has access to only one point of view at a time (either the geocentric or the “space-based” (allocentric) perspective, depending on his or her position and role in the model). We suggest that using a casting device and a smartphone or tablet to project in real-time one perspective on the model on a screen or TV, while students have direct access to another point of view (their own), is a good way to help them switch and compare both perspectives simultaneously and build a better understanding of the astronomical phenomenon under study.

But we will also insist on the importance of first providing students with enough first-hand experience with the geocentric view on the phenomenon under study, as it is a necessary condition if the model is to help them construct a better understanding of the mechanism responsible for what we see from Earth. Lucas & Cohen (1999) suggest that knowledge based on direct observation constitutes an essential foundation for students to understand the scientifically accepted explanation for astronomical phenomena. As summed up by Plummer, Wasko and Slagle (2011) “first, [students] must visualize the apparent motions of these objects, from their own perspective. Second, they must also imagine a new space-based perspective from which to explain why celestial objects appear the way that they do as seen from the Earth.” (p. 1964) What we propose here is that students do not have to “imagine” any new perspective, since they can access both point of view directly with the aid of simple and affordable casting technology, coupled with a TV monitor or video projector.

## 3 A three-step method to teach astronomical concepts in the classroom with casting technology

In the following sections, we will describe a three-step approach to teach astronomical concepts that several authors have identified as best supported by the use of concrete models in the classroom: the diurnal cycle, phases of the Moon and eclipses, the seasons, and planetary motion. For each topic, we will first describe how to facilitate direct (or mediated through the use of software) observation and experience of the phenomenon by students from an Earth-based perspective (i.e., the geocentric view), then how to model the phenomenon in the classroom using concrete objects, and finally how a casting device and smartphone's or tablet's camera can be used to show students a

new perspective on these models simultaneously via a TV monitor or a video projector.

### 3.1 Diurnal cycle

Observation of the diurnal cycle (i.e., the cycle of day and night) is straightforward and it can be assumed that every student, even the youngest, has had plenty experience with the Sun rising in the East, moving across the sky during the day and setting in the West. This is obviously due to the Earth's rotation on its axis in one day from West to East (i.e., counterclockwise as seen from a point located high above the Earth's North Pole). The Earth being a solid sphere lit by the Sun, there is always half the Earth in sunlight (i.e., the day side) and half in the shadow that the Earth casts on itself (the night side, i.e., its self-shadow, see Young & Guy, 2008). As the Earth spins on its axis, every point on the surface translates from the day side to the night side and back in a 24-hour period. But since the rotational motion of the Earth is imperceptible to us, frequent misconceptions attribute the apparent motion of the Sun across the sky to the revolution of the Sun around the Earth, or some variation of motion of the Sun about the Earth (see Vosniadou & Brewer, 1994). It is interesting to note that the Sun's revolution about a fixed Earth has been the canonical explanation for the diurnal cycle for millennia, and only relatively recently has the Copernican revolution changed the way we conceptualize the day-night cycle (see Crowe, 2001; Kuhn, 1957).

The observation of the diurnal cycle is so common that it may seem implied. One way to make this observation explicit is by using a simple gnomon or sundial, and have students follow the course of the Sun across the sky for one day. In a study about the teaching of seasons, Plummer & Maynard (2014) used clear plastic hemispheres set on a flat, level surface on which students would trace the apparent path of the Sun at different moments of the year to study the seasonal shift of the Sun's daily path; this method would also work well to study the apparent motion of the Sun across the sky on a clear, sunny day by marking the Sun's position on the dome every hour or so.

To demonstrate the diurnal cycle in the classroom, it has been proposed to identify one's location on an earth globe with a small sticker, a figurine or a pin, and shine a bright light on it in a darkened room to create a bright hemisphere and a dark one (i.e., day and night, see Sneider, 1998). By rotating the globe counterclockwise as seen from above the North Pole, one can easily see that each location on Earth alternatively passes through the lit and dark hemispheres of the Earth, hence creating the alternating day and night. Another approach proposes that each student individually experiences modelling the Earth's actual rotation by rotating on him or herself in front of a light source representing the Sun (Diakidoy and Kendeou, 2001; Sharp and Kuerbis, 2005).

The use of a smartphone's camera attached to the rotating earth globe (for example, with a Velcro strip glued to the back of the phone, see Figure 2) and projecting the image on a nearby screen while students form a circle around the Sun-Earth Model, is a good way to help them connect their own space-based view with what an observer on Earth (i.e., the camera) would experience at the same time. Another approach is to ask a volunteer (or the teacher) to hold a phone or tablet and rotate in front of a light source, again demonstrating the diurnal cycle. Prompt questions associated with such demonstrations could be "In what direction must the Earth spin on itself to show the Sun 'moving' from East to West?" (a: counterclockwise as seen from above the North Pole), "Above what direction on the horizon will the Sun be in the sky at noon?" (a: toward the South in the north-

ern hemisphere, toward the North in the southern hemisphere), "Where is the Sun at night?" (a: it is behind the Earth, blocked from view by the solid Earth).

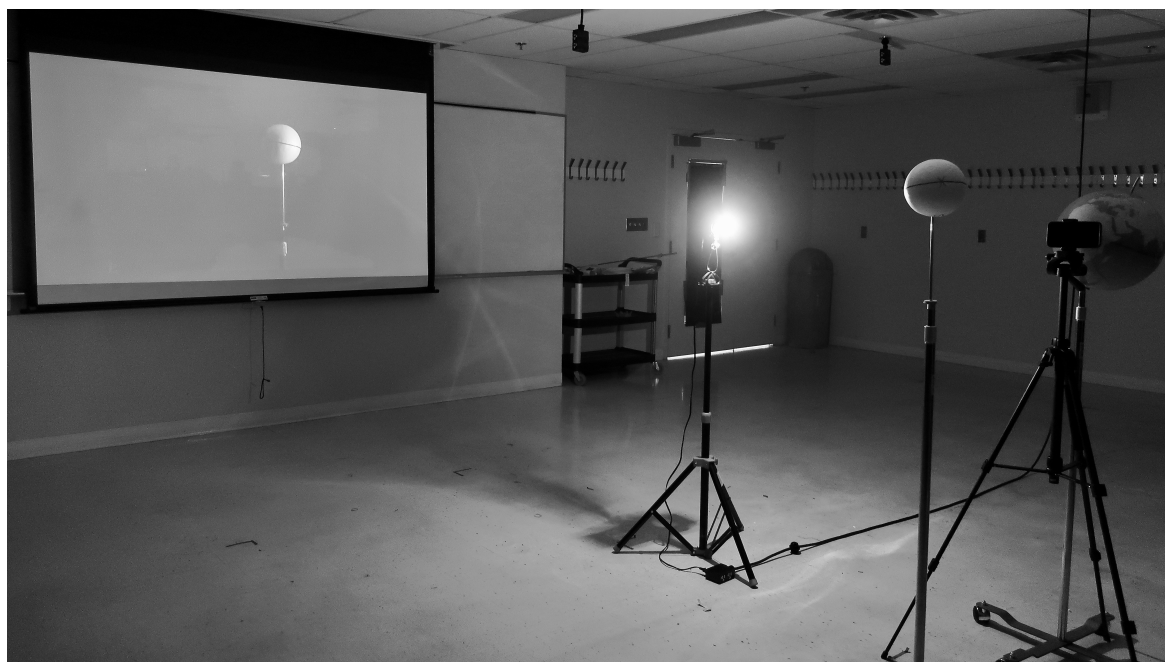
### 3.2 Phases of the Moon and eclipses

Phases of the Moon is one of the most challenging topics taught in elementary, middle and high school astronomy classrooms, and a vast number of misconceptions have been uncovered among students as well as teachers (see appendix in Chastenay & Riopel (2020) for a comprehensive list of the most common misconceptions about lunar phases). To understand lunar phases, one must first realize that the Moon is a solid sphere lit by the Sun, hence half of the Moon is bright with reflected sunlight, and half is dark because of the shadow the Moon casts on itself (its self-shadow). One must also understand that the Moon revolves around Earth in about 30 days (the synodic month) and that, as the Moon travels along its orbit, we see the illuminated half of the Moon at different angles, which causes the phases. The phase of the Moon can be defined as the percentage of the illuminated half of the Moon that is visible from Earth, and it changes as the Moon revolves around the Earth from 0% (new moon) to 100% (full moon).

Studying the lunar phases from a geocentric point of view can best be achieved by using a blank "Moon calendar" that students must fill each day with various information about the Moon, drawing its phase, recording rise and set times, illumination and elongation, etc. (see Kavanagh et al. (2005), Chastenay & Guay-Fleurent (2022) and Chastenay et al. (2023) for a complete description of this method). Unfortunately, bad weather, and the Moon rising too late for younger students to see it at night, might prevent seeing the Moon over several days; in these cases, astronomy apps for smartphones and tablets, and planetarium software (Persson and Eriksson, 2016) can easily compensate. The free planetarium software Stellarium® for Mac and PC (<https://stellarium.org>; also accessible online at <https://stellarium-web.org/>) provides a wealth of information about the Moon as it changes from day to day, information that students can then report on their Moon calendar to have a continuous record of the evolution of lunar phases over the course of one month.

Trundle & Bell (2003) have studied the use of the planetarium software Starry Night™, a package quite similar to Stellarium®, to facilitate the gathering of data about the lunar phases. Bell & Trundle (2008) and Trundle & Bell (2010) also studied the use of this software by early childhood pre-service teachers and found it to be as effective as direct observation of the Moon in promoting understanding of lunar phases. Hobson, Trundle & Saçkes (2010) showed that a computer simulation like Starry Night™ enabled even younger children, aged 7 to 9 years old, to better understand the lunar phases.

As for concrete models to teach the lunar phases in the classroom, the most common model uses a Styrofoam ball on a stick to represent the Moon, a single light bulb in a darkened room for the Sun, and the students' head for the Earth (see <https://www.jpl.nasa.gov/edu/teach/activity/moon-phases/>). By holding the ball at arm's length in front of them and rotating toward their left, students will easily recreate the sequence of phases as they observed them over a month, thereby demonstrating the mechanism of lunar phases. Several research studies reported in Kavanagh et al. (2005) considered the effectiveness of this approach to address students' ideas about the phases of the Moon, and support the conclusion that teaching methods based on modelling lunar phases are more effective than direct instruction approaches alone (textbook, illustrations, etc.).



**Figure 1.** In this setup, an iPhone on a tripod located close to an Earth globe captures the geocentric perspective on the Moon, casted on a screen via an AppleTV and a video projector. As seen from an allocentric perspective (picture above), the aspect of the Moon is quite different from the last quarter phase seen from Earth and projected on the screen. Photo: Author.

Examples of studies that have followed the same general strategy described above to teach the phases of the Moon to learners of different age groups include: Trundle, Willmore & Smith (2006b), who worked with children in grades 4 to 8; Trumper (2006) with future elementary and junior high school teachers; Trundle, Atwood & Christopher (2006a; 2007b) with pre-service elementary teachers; Trundle, Atwood & Christopher (2007a) with fourth-grade students; Mulholland & Ginns (2008) with pre-service teachers; Trundle et al. (2010) with middle school students; Chastenay & Guay-Fleurent (2022) with pre-service high school teachers; and Chastenay et al. (2023) with in-service late elementary and early high school teachers and their students. All these studies show a better understanding of the lunar phases after instruction using a similar modelling approach, compared to direct instruction using textbooks.

Sensing the difficulty students had switching frames of reference on astronomical systems using such a model, Suzuki (2003) worked with pre-service teachers who came up with the idea of attaching a small video camera to a rotating earth globe to help explore the phases of the Moon, eclipses and the changing time of day and night that our satellite is visible over the local horizon, whereas Sherrod & Wilhelm (2009), working with seventh-grade students, used two Styrofoam balls, one for the Moon and one for the Earth, in conjunction with a bright light source, thus encouraging students to switch from a geocentric to an allocentric, space-based point of view on the Sun-Earth-Moon system.

To show different perspectives on lunar phases with a smartphone or tablet using the simple Styrofoam-ball model, students working in pairs can film either the view from Earth, by holding the camera in front of their face while holding a Styrofoam ball at arm's length, or the view from space, by handing the camera to the other student, thus providing the allocentric view at the same time (Figure 1).

The Styrofoam-ball model for the lunar phases is rather crude and limited; it can be upgraded by asking students to participate in a human orrery representing the Sun-Earth-Moon system in a darkened classroom. A piece of rope forming a circle on the floor around the Earth will represent the lunar orbit, and a naked light

bulb in a corner of the room will represent the Sun. Choose a rope roughly 10 m (30 ft) long and attach a marker on the rope every 30 cm (1 ft) to mark the Moon's position on its orbit every day. Two students are part of this model, one holding a large, white ball to represent the Moon as he or she is moving along the rope, and one at the centre of the Moon's orbit representing the Earth and holding a smartphone or tablet; the other students are forming a large circle around the model, experiencing the view from space. By projecting the view from Earth on a screen with the smartphone or tablet, students experience both the geocentric and the allocentric views as the Moon revolves around Earth and its phase changes.

Adding rotation of the student representing Earth and holding the camera (i.e., one rotation while the Moon advances to the next marker on the rope, about 1/30th of the perimeter of its orbit) will allow students to see how the rise and set times of the Moon change with its phase. Students can be prompted to predict the next phase before the Moon advances on its orbit, or the time it will rise and set the next day (i.e., about an hour later). Mechanisms for lunar and solar eclipses arise naturally from the model, and one can ask the student holding the Moon to "tilt" the Moon's orbit slightly, holding it above his or her head on half of the orbit, then at chest level on the other half, to explain why we don't see eclipses every month. The student representing the Moon can also be asked to hold the camera and film an earth globe located at the centre of the orbit as he or she is revolving around it, thus showing phases of the Earth as seen from the Moon, an occurrence that will probably surprise a lot of students. The same model can be used to study phases of the moons of Mars or Jupiter, thus generalizing the mechanism of phase formation to every situation where a solid, opaque object is lit by a distant source of light and seen at various angles. The same can be said of the phases of Mercury and Venus, as we will show in section 3.4.





**Figure 2.** An iPhone is attached to an Earth globe via Velcro, allowing to position the camera of the phone at different latitudes. By moving the Earth globe around a source of light representing the Sun, but always keeping the North pole pointed in the same direction, one can see the difference in the Sun's height above the horizon from season to season (see Figure 3). Photo: Author.

### 3.3 Seasons

The seasons are another difficult topic to be taught in school, due to the ubiquitous and very robust misconception that seasons are due to the variation of the distance between the Earth and Sun, and also because of the highly complex spatial nature of the mechanism for the seasons. In fact, according to Plummer (2012), “it seems likely that learning to explain the seasons is more difficult than learning to explain the phases of the moon.” (p. 83) Seasons are due to the tilt of the Earth's axis of rotation of roughly 23.5 degrees to a perpendicular to the plane of its orbit around the Sun. Also, notwithstanding precession, the orientation of this axis is fixed in space relative to the stars, i.e., it always points in the same direction (toward the star Polaris in the Northern hemisphere). But as the Earth revolves around the Sun in one year, the inclination of its rotational axis changes *relative to the Sun*: at one point, the North polar axis leans toward the Sun while the South polar axis leans away from it (Summer solstice in the North, Winter solstice in the South). Six months later, the reverse occurs. At mid-point between these extremes, the polar axis is perpendicular to a line drawn between the Earth and the Sun (equinoxes) and the seasons are similar in both hemispheres.

As seen from Earth, the Earth's revolution around the Sun and its tilted axis are responsible for the changing length of day and night, the varying height of the midday Sun above the horizon and, accordingly, the changing amount of heat transferred to different parts of the planet's surface as the angle of incidence of Sun rays' on the ground changes. When the days are long, the Sun is high in the sky for a longer period of time and the heat transfer is at its highest; it's Summer. Also, longer days mean more time for heat to be transferred. On the contrary, when days are short, the Sun is low and heat transfer is minimum (and shorter in duration): it's Winter.

The seasons, like the apparent motion of planets across the sky (see next section), are special cases where direct observations by the students are possible, but the long duration and slow progress of these phenomena makes it impracticable for students to observe them in a short period of time. We already mentioned the study by Plummer & Maynard (2014), inspired by Gould, Willard & Pompea (2000), in which clear plastic hemi-

spheres were used to trace the apparent path of the Sun at different moments of the year. This activity takes months to complete, whereas a planetarium software like Stellarium® allows students to explore these phenomena in a more suitable time frame.

To study the seasons, students should be instructed to use a planetarium software set to their location to observe the rising and setting time and azimuth of the Sun, calculate the length of day, as well as measure the Sun's height at noon, at different moments of the year (for example, once a week or twice a month), including solstices and equinoxes. What's more, they should be instructed to carry the same observations and measurements from another place on Earth located at the same longitude and latitude, but in the other hemisphere. They should also be encouraged to look for climate data for each location, to compare mean temperatures, precipitations, etc. for both locations from season to season (see Chastenay, 2023, accepted).

The comparison of the Sun's daily apparent path across the sky and the local weather between two similar locations in different hemispheres, equidistant from the equator, will show that seasons are inverted from one hemisphere of the Earth to the other, an important realization that is directly in contradiction with the most prevalent misconception about seasons, i.e., that it is caused by the distance variation between the Earth and the Sun. Indeed, if the changing Earth-Sun distance was responsible for the change in seasons, both hemispheres of the Earth would experience the same season at the same time. What's more, and this is especially relevant for people living at mid-latitude in the Northern hemisphere, the Earth is closest to the Sun around January 4th, one of the coldest months of the year, and farthest on July 4th, in the middle of Summer in the Northern hemisphere.

Teaching the seasons has been reviewed by Sneider, Bar & Kavanagh (2011). They propose a learning progression for the seasons that emphasises the need for students to first gain some familiarity with the phenomenon as seen from Earth, and then use concrete models to better understand the mechanism of seasonal changes. Covitt et al. (2015) also used a scientific modelling sequence informed by observations to teach the seasons to in-service elementary and middle-school teachers participating in a summer graduate-level astronomy course. They found that teachers who experienced the modelling-focused sequence demonstrated large gains on assessment questions.

A terrestrial globe mounted on a rolling cart, and a light bulb in the centre of the room representing the Sun, remain the best model to demonstrate the mechanism of the seasons in the classroom. Earth globe models without an arch joining the poles work best. For optimal results, make sure that the source of light is level with the centre of the globe. It is also important that, while revolving around the Sun on the cart, the globe's axis remains pointed in the same direction (i.e., tilting toward the same wall), otherwise the demonstration will be flawed. A sticker, a pin or a small figurine fixed on their own location on the globe will help students figure out what's happening where they live in terms of illumination, length of day and angle of incidence of Sun rays as the Earth spins on its axis at different points on its orbit. A second marker at the same longitude and latitude in the other hemisphere will help compare situations in both hemispheres at once.

It is possible to attach a smartphone to the surface of the globe at different locations in both hemispheres to provide the geocentric view that will complement the view students have while standing around the model (Figure 2). For instance, if the phone is fixed on a location at mid-latitude in the northern hemisphere and the globe's North pole is leaning toward the light bulb, the bulb will appear to rise higher in the image cast by the phone than if the globe is moved to the other side of the light

source (i.e., North pole leaning away from the bulb), whereas the bulb will remain low in the casted image (Figure 3). The same demonstration can be made for the southern hemisphere; in that case, one has to remind the students that they have to look at the projected image upside-down.

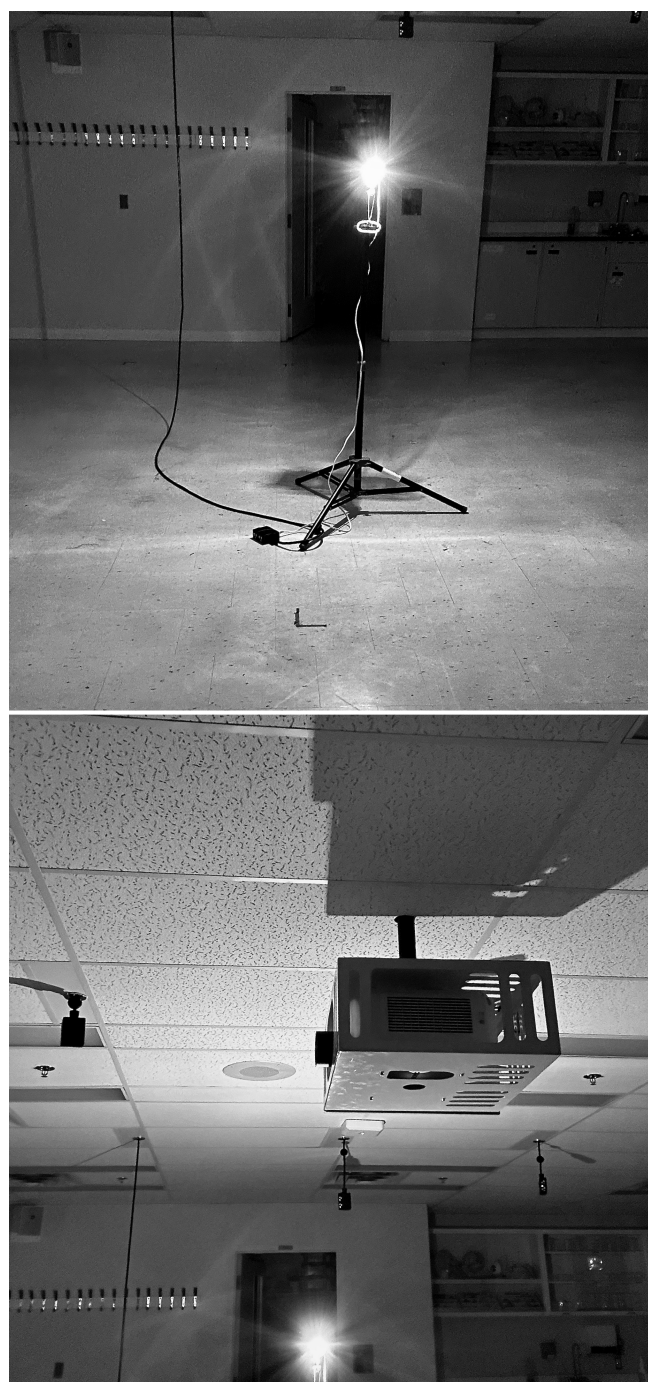
“What if” questions are interesting to discuss with students at this point using the model: What if the axis of rotation was not tilted, but rather perpendicular to the orbital plane? It’s easy to demonstrate that for each location on Earth, the length of day, height of the midday Sun and angle of incidence of sunrays would be constant from day to day. The only variation remaining would be due to the very small variation in distance between the Earth and Sun (about 3% between perihelion and aphelion, not enough to cause large seasonal variations). What if Earth’s rotational axis lied in the orbital plane (i.e., a tilt of 90 degrees)? A demonstration with the earth globe would show that seasons would be extreme, as the North and South poles would alternatively become the hottest and coldest places on Earth over the course of a year. This is exactly the case for the planet Uranus, whose axis of rotation is tilted 98 degrees to a perpendicular to the plane of the ecliptic, over the course of its 84-years orbit. A similar demonstration can be made with a globe representing the planet Mars, whose axis of rotation is also tilted (25 degrees). Mars experiences contrasted seasons as it revolves around the Sun, much like Earth, as demonstrated by the expansion and recession of its polar ice caps.

### 3.4 Apparent motion of planets

Apparent motion of planets is a topic much less taught in elementary, middle and high school than the concepts presented in the previous sections, and much less studied by science education researchers working at these school levels. The topic seems to be favoured by researchers working with undergraduates, like college physics students (see Pincelli & Otranto, 2013; Thompson, 2005; Yu, Sahami & Denn, 2010). For one, the study of the solar system in elementary, middle and high school usually deals with physical and orbital characteristics of the planets, without any attempts to establish a link with observations that students might have made prior to study. Second, observing the planets in the sky is a challenge for teachers and students alike: planets are usually only visible at night, outside of school hours, and one needs a good knowledge of star patterns and night-sky orientation to be able to locate planets among the stars. Finally, to observe the slow apparent movements of the planets, like retrograde motion of Mars, one must observe regularly over an extended period of weeks to months, a difficult task in any circumstance, even more so in a school setting.

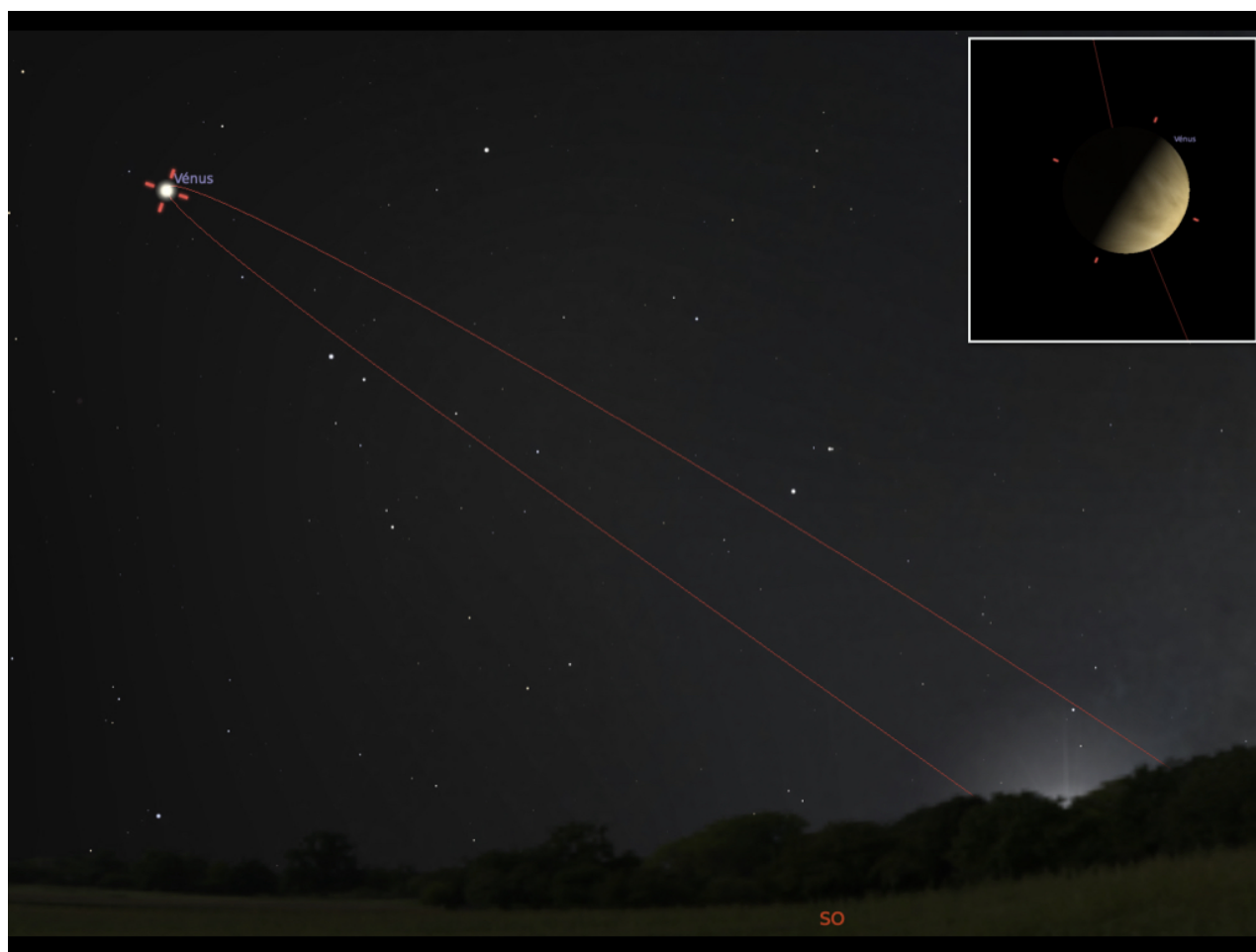
Planets in the solar system can be grouped in two categories according to the position of their orbit relative to Earth’s orbit: inferior planets, whose orbits are smaller than Earth’s (i.e., Mercury and Venus), and superior planets, whose orbits are larger than Earth’s (Mars, Jupiter, Saturn, Uranus and Neptune). As seen from Earth, these two groups behave very differently, and their apparent motions are quite distinctive. Inferior planets never stray very far from the Sun and are best viewed in the west after sunset (greatest eastern elongation, see Figure 4) or in the east before sunrise (greatest western elongation). In between, inferior planets are in conjunction (inferior when they pass between Earth and Sun, superior when they pass behind the Sun) and thus invisible, except for rare transits, when Mercury or Venus in inferior conjunction appear as a small dot crossing the Sun’s surface.

Superior planets can be in conjunction (behind the Sun and invisible) or in opposition (opposite to the Sun in the sky and



**Figure 3.** Images of a lamp representing the Sun as captured by an iPhone attached to an Earth globe at mid-latitude in the Northern hemisphere. In top image, the Northern hemisphere of the Earth globe is leaning toward the Sun (i.e. Summer in the North), thus the Sun appears higher in the sky than in the image on the bottom, where the Northern hemisphere is leaning away from the Sun (i.e. Winter in the North). Photos: Author.

closest to Earth). Superior planets are best viewed at opposition, when their apparent diameter and brightness increase considerably. It is also in opposition that superior planets go through retrograde motion. As seen from Earth, and relative to background stars, a superior planet about to reach opposition will appear to slow down in its eastward movement, stop, move backward (westward) for some time, stop again and resume its eastward movement, its path drawing a kind of loop relative to the background stars (Figure 5). This retrograde motion is similar to a fast car overtaking and passing a slower vehicle on the highway: as the faster car passes the slower one, the latter



**Figure 4.** A screen grab from Stellarium showing the orbit of planet Venus at greatest eastern elongation. Insert: The phase of Venus at greatest eastern elongation (compare with projected image in Figure 6). Source: Stellarium.

seems to be moving backward relative to houses and trees lining the highway. Since Earth travels faster on its orbit than all the superior planets, every opposition means retrograde motion. Mars, being the closest superior planet to Earth, exhibits the largest retrograde motion (largest loop), that can be seen about every 26 months (Figure 5). For the other superior planets, retrograde motion is much smaller and takes a little more than a year to repeat.

Providing a geocentric perspective on apparent planetary motion for teaching purposes is restricted by the same limitation as the seasons, i.e., it is a celestial phenomenon that evolves slowly and it takes weeks or months of precise observations to see changes in a planet's position among the stars. When such a long period of time is impracticable for teaching purposes, planetarium software like Stellarium© allows speeding up time to show in a few minutes planetary motions that usually spans several months. Stellarium© is especially well suited for this when one uses the Shift+T command to show planets trails (Figure 5). The elongations of Mercury and Venus east and west from the Sun become readily apparent (one can even measure the elongation angle using Stellarium's protractor tool), as is the retrograde motion of the naked-eye planets Mars, Jupiter and Saturn.

Finally, a great way to model planetary motion in the classroom is by creating a human orrery with the students, an activity described by Bailey et al., (2005); Newbury, (2010); and Thompson, (2005). Three pieces of rope, each forming a circle of different diameter, are laid on the ground to form three concentric rings centred on a lightbulb representing the Sun. The

shortest rope is the orbit of an inferior planet, let's say, Venus, with a perimeter of 6,8 m or 22 ft. For the sake of simplicity, there is no need to represent Mercury's orbit as well, as the demonstration with Venus is representative of both planets. The longest rope represents a superior planet (Mars, in this case, with a circumference of 14,3 m or 47 ft). The rope in the middle is the Earth's orbit, 9,4 m or 31 ft in circumference. A series of markers on the ropes represent the relative position and speeds of each planet. For Venus, 16 markers are set at 42 cm interval; Earth's 26 markers are 36 cm apart, while for Mars, 50 markers are 29 cm apart. Each marker represents the orbital displacement of each planet over two weeks (Figure 6).

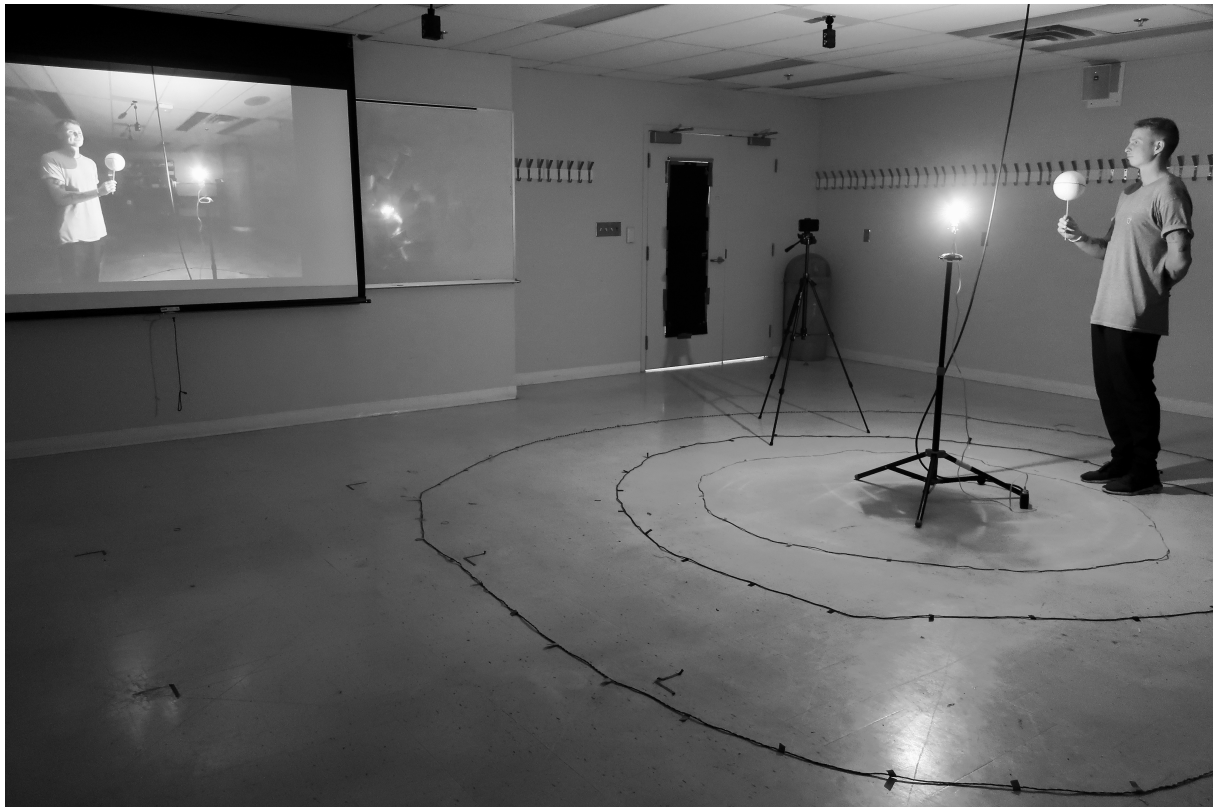
Three students participate in the human orrery, one representing Venus, one the Earth and a third, Mars. It would help that each student holds a coloured ball for identification: yellow for Venus, blue for Earth and red for Mars. It is important that each student steps from one marker to the next in step with the others; this will clearly demonstrate that Venus revolves around the Sun faster than the Earth, which in turn revolves faster than Mars.

After one or two complete revolutions of Mars, students should start exploring the apparent motions of Venus and Mars as seen from Earth, using a camera showing the Earth-centered perspective, while the rest of the class looks on "from space". This will help students make sense of the seemingly random movements of the planets in the Earth's sky. Elongations of Venus (and Mercury), and the retrograde motion of Mars (similar for Jupiter or Saturn), all become easy to explain once students have access to both perspectives (geocentric and allocentric) in a dy-





**Figure 5.** A screen grab from Stellarium showing the retrograde motion of planet Mars in 2024-2025. Source: Stellarium.



**Figure 6.** Eastern elongation of Venus as seen from an allocentric point of view (i.e. from "space"), while an iPhone on a tripod projects the geocentric view on a screen. The image projected on the screen shows the phase of Venus as seen from Earth at this point of the planet's orbit (compare with insert in Figure 4). Photo: Author.



dynamic demonstration of the inner workings of the solar system. Also, as a bonus, one can use this model to illustrate phases of the inferior planets (Mercury and Venus) as they revolve around the Sun as viewed from Earth. The illustration of phases of the inferior planets, as well as the demonstration of phases of the Earth as seen from the Moon, should help students gain an even better understanding of the phase's mechanism, as well as its ubiquity in the solar system.

## 4 Conclusion

We are watchers of the sky, confined to the surface of a vast, spherical observatory that's hurtling through space, spinning on its axis once a day and revolving around the Sun once a year at incredible speed. At the same time, the Moon travels around the Earth once a month (roughly twelve times a year) on an invisible orbit. The planets are also in motion, traveling about the Sun on their own, invisible orbits and drawing complicated trajectories on the fixed pattern of distant stars. All these motions are completely oblivious to us, and without the ability to break free from the confines of our planet's surface to watch this astronomical clockwork from afar and link the geocentric view with the view from space, it might prove impossible to comprehend the mechanics behind all these real and apparent motions.

Concrete models that one can manipulate in the classroom have proven to be effective at providing students with both perspectives, the view from Earth and the view from space, on dynamical astronomical systems. Coupled with prior geocentric observations that give students ample experience with the Earth-based aspects of the phenomenon under study, these models and the allocentric point of view they afford help students switch between perspectives, thus providing scaffolding to build a correct mental model of the mechanism behind these apparent motions.

Unfortunately, it is impossible for each and all students in a typical classroom to be able to experience both perspectives on the model at once, unless one uses a smartphone or tablet and a casting device so that both points of view, Earth-based and space-based, are available at the same time simply by looking at the model, then at a TV monitor or screen showing the other point of view. It's a simple and affordable addition to existing models that might make a huge difference in the understanding of students and teachers of the often-complicated mechanism of common astronomical phenomena.

Let us again emphasize the importance of developing in students a large knowledge-base of experience in observing the phenomenon under study from a geocentric perspective before introducing models to explain what was observed. As Plummer (2017) wrote, "beginning with children's own Earth-based observations of celestial phenomena is an important foundation for their understanding of astronomy; they must first develop an understanding of astronomical phenomena before later learning how to explain those observations. This process mirrors the way scientists work by first recognizing and studying a phenomenon and later trying to explain it using scientific principles and theories." (p. 189)

The practical suggestions made in the present paper have not yet been put to the rigorous test of implementing them in the classroom to measure learning gains or the evolution of misconceptions among learners. The author has tested these ideas in his own science and astronomy methods course with pre-service high school teachers, and anecdotal evidence suggests that this approach is beneficial to students as it helps them switch almost instantaneously from one point of view to the other. It seems students don't have to imagine what the world would look like

from another point of view: it's there for them to see, simply by turning their heads toward a screen showing the "other" point of view. But this proposition needs to be rigorously tested.

There are of course several practical issues to be considered here: for instance, the TV monitor or the video projected on a screen is an important source of light that can completely ruin the model studied, especially if one teaches the diurnal cycle or the lunar phases, where the contrast between the lit side of the earth globe or ball representing the Moon and its dark side is crucial if the model is to make sense for students. Testing with different light bulbs or a rheostat and reducing the brightness of the projection will all help toward finding the right balance. Obviously, this will work best in a darkened room, ideally without window.

Future research should focus on documenting the educational benefits of using a smartphone or tablet, a casting device, and a TV monitor or video projector in the classroom, on the understanding of the mechanisms of common astronomical phenomena by students and teachers. Anecdotal evidence points toward real benefits, as the technology can scaffold the experience of switching perspectives on several astronomical models, but a rigorous research programme could turn anecdotes into science education results that will benefit the whole community of astronomy educators worldwide.

## 5 Declarations

### 5.1 Ethical Considerations

Not applicable.

### 5.2 Consent for Publication

Not applicable.

### 5.3 Competing Interests

The authors declare that they have no competing interests.

### 5.4 Funding

Not applicable.

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