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RESEARCH ARTICLE

PD Days Under the Moon: Teaching Lunar Phases to In-Service Teachers by Doing Astronomy Like Astronomers Do and its Impact on Their Students' Learning

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Abstract

Several school curricula urge K-12 teachers to engage their students in scientific inquiry activities that not only promote students' learning in science, but also foster students' understanding of science methodology. Unfortunately, recent large-scale studies have shown that inquiry-based science teaching in school is the exception, rather than the norm. This is especially true for astronomy, which teachers often consider too abstract and remote for inquiry-based teaching. To promote inquiry-based teaching in astronomy, we present an epistemological and historical analysis of the way astronomers build new knowledge and propose to teach astronomy through a scientific inquiry process consisting of "Doing astronomy like astronomers do". This inquiry-based approach, which also includes observation, modelling, and communication with peers, emulates the different steps astronomers and scientists go through to do empirical science (question, hypothesis, observation, analysis/synthesis, modelling, prediction/application, and communication), transposed into a teaching and learning lesson plan about the phases of the Moon. The crucial steps of observation, analysis/synthesis, and modelling, where astronomers create models as proxies of astronomical objects that cannot be manipulated, is highlighted. This inquiry-based astronomy training, which also promotes conceptual change about lunar phases, was tested with 18 in-service elementary and high school teachers engaged in a professional development (PD) training program. Three participant teachers also taught lunar phases to their own elementary and high school students (N = 104) using the same approach. We present the results of a quasi-experimental study of the impacts of this PD training about lunar phases on the learning gains and self-efficacy of the participating in-service teachers, as well as on their students' learning.

Keywords: Conceptual change, In-service teacher training, Modelling, Phases of the Moon, Scientific inquiry, Self-efficacy

1 Introduction

Contemporary research in science education aimed at teaching science concepts in K-12 classrooms recommends that teachers move away from "rote" learning, and lead students in engaging scientific activities that not only promote students' learning of the science content under study, but also foster students' understanding of science methodologies (Sikorski and Hammer, 2017). This is also how recent curricula and reformed school programs recommend that science be taught. For instance, *A Framework for K-12 Science Education* (NRC, 2012, 2000) calls for teaching strategies that include scientific inquiry practices in the classroom, practices that engage students in the thinking processes and activities of scientists (Rönnebeck et al., 2016). The *Next Generation Science Standards* (NGSS Lead States, 2013) suggest that students be actively engaged in building their own understanding of scientific knowledge by practicing scientific inquiry. In addition to the United States, several member countries of the Organisation for Economic Co-operation and Development (OECD) have recently updated their K-12 science curricula to include more scientific inquiry in the classroom (Salimpour et al., 2021), including Australia (ACARA, 2017), Québec (Ministère de l'Éducation du Québec [MEQ], 2006a,b; Ministère de l'Éducation, du Loisir et du Sport, 2007) and the United Kingdom (United Kingdom Department of Education, 2013a,b, 2014). There is widespread agreement that students should be able to engage in scientific inquiry in the classroom to enhance their learning in, and of, science. To achieve this goal, teachers must implement effective, inquiry-based science lessons that provide opportunities for students to develop a deeper understanding of how science works.

Unfortunately, inquiry-based science teaching in elementary classrooms seems to be the exception, rather than the norm. For example, in the United States, the sixth edition of the National Survey of Science and Mathematics Education (NSSME+) found that a majority of elementary teachers still mainly use science textbooks to teach science in their classroom (Banilower et al., 2018; Plumley, 2019), a result that has remained more or less constant over the last 40 years (see `http://horizon-research.com/NSSME/`). Similar results were found by Rowell and Ebbers (2004) in Alberta, Canada, and across four decades by the Conseil supérieur de l'éducation 1982; 1990; 2013 in Québec, Canada. A recent survey conducted by the author with 638 elementary teachers found that most teachers use textbooks and exercise books almost exclusively to teach science to their students, thus transforming the study of science content into a reading and writing exercise (Chastenay, 2014, 2018; Chastenay and Riopel, 2019).

It is possible to transform the way science is taught in elementary classrooms by providing teachers with professional development (PD) programs that aim at "engaging teachers in investigations, both to learn disciplinary content and to experience inquiry-oriented learning." (Banilower et al., 2018, p. 51)Many examples of successful training about inquiry-based teaching for pre-service teachers can be found in the literature, but studies of similar training aimed at in-service teachers are less common. One example is Murphy et al. (2015), who showed how a continuous PD program conducted over two years with 17 primary teachers has led these teachers to shift their "traditional, didactic, theory-laden views of science teaching" (p. 1) toward more inquiry-based methodologies and develop their own confidence in using more inquiry-based approaches to teach science in their classroom.

1.1 Inquiry-Based Teaching in Astronomy

In the survey conducted by Chastenay 2014; 2018 and Chastenay and Riopel 2019, elementary teachers were also asked about their teaching of astronomy topics in their classroom. About half admitted never teaching astronomy to their students, even though topics like the diurnal cycle, phases of the Moon, the seasons, and the solar system are all part of the curriculum for elementary schools (Ministère de l'Éducation du Québec [MEQ], 2006a). When asked why they do not teach astronomy at all, most teachers blamed poor or non-existent pre-service and in-service training in astronomy, a perceived lack of knowledge and skills to teach astronomy to their students along curriculum guidelines, including inquiry-based strategies, as well as their perception that astronomy is simply not suited for inquiry-based teaching, contrary to physics or chemistry. Astronomy as a school topic is considered too abstract and remote to lend itself to any teaching method other than textbook and exercise book (Chastenay, 2018).

Yet, according to Plummer and Tanis Ozcelik (2015), teaching astronomy through inquiry in elementary classrooms is indeed possible, if one defines scientific inquiry as a way to give students the opportunity to state a scientific question or problem, plan and carry out an investigation (including observation), engage in using models to construct evidence-based explanations for a scientific phenomenon, and communicate and justify explanations to their peers. Applying this inquiry-based approach with 30 pre-service elementary teachers engaged in a science methods course, the authors had their students participate in astronomy investigations about celestial motion (diurnal and seasonal apparent motion of the Sun and stars, and the lunar phases), and then develop lesson plans to teach inquiry-based astronomy about these topics to elementary students engaged in afterschool programs. The preservice teachers made observations, developed representations and models of how celestial objects move, for example using a globe and a lamp to explain the Sun and stars' apparent motion, and developed explanations for these phenomena.

Results show that this inquiry-based teaching of astronomy led to a significant increase in content knowledge of pre-service teachers about the astronomical topics covered in their lesson plans, and a more coherent view of scientific inquiry applied to astronomy education for a majority of participants, albeit with varying degree of mastery from one lesson plan to another. The authors attribute their students' success to the focus on a single topic, observational astronomy, and the fact that teachers learned astronomy investigations first-hand, and were then able to immediately apply what they had learned by developing lesson plans and teaching astronomy to elementary students. This conclusion is congruent with Bandura (2000), who noticed that teachers who actively engage in applying skills and knowledge gained during their own learning are more likely to implement them in their classrooms.

Inspired by Plummer and Tanis Ozcelik's (2015) approach, we have designed and tested an inquiry-based PD training program in astronomy for in-service elementary and high school teachers about the phases of the Moon. The PD training program is based on an epistemological and historical analysis of the way professional astronomers produce new knowledge about astronomical phenomena. We propose that astronomers conduct their research following the same steps as other scientists doing empirical research (question, hypothesis, observation, analysis/synthesis, modelling, prediction/application, and communication), but with the crucial difference that for astronomers, observation is the only mean of gathering information about celestial objects and events, and modelling serves the dual purpose of reproducing observations and allowing the manipulation of variables to help understand the processes behind the phenomena observed. Ultimately, our inquiry-based approach leads teachers to develop content knowledge and teaching skills in astronomy by "Doing astronomy like astronomers do", as part of a scientific inquiry process that includes observation, modelling and communication with peers and students (Hasni et al., 2018; Windschitl et al., 2008).

In this paper, we will detail the epistemological and theoretical foundations of our teaching strategy and its links to the process of conceptual change. We will outline how we transposed the way professional astronomers produce new knowledge in astronomy in the context of a two-day PD training program aimed at in-service teachers to help them teach the phases of the Moon to their students. We will also present the results of an empirical study measuring the effects of this training on the content knowledge and self-efficacy in astronomy teaching of participant teachers, as well as on their students' learning in astronomy. In conclusion, we will discuss ways to use a similar approach to teach other basic astronomical concepts, like the diurnal cycle, the seasons and planetary motion.

2 How Do Astronomers Do Astronomy?

The analysis of the historical development of scientific knowledge, and the epistemological study of the construction of new knowledge by the community of researchers in astronomy, and in fact scientists in general, teach us that the starting point of any scientific investigation is natural curiosity about the working of the natural world, which can then be expressed as a question. As the French philosopher of science Gaston Bachelard wrote, "for a scientific mind, all knowledge is an answer to a question. If there is no question, there can be no scientific knowledge." (1938, p.14, free translation). But the question must be operationalized to make it a genuine research question. This operationalization process involves the production of hypotheses, which are provisional explanations based on the current knowledge of the community of researchers, as well as their intuitions, and which attempt to answer the initial question. Then, astronomers choose the instruments that will facilitate the collection of data needed to sort out different hypotheses.

As noted by Giordan (1999), astronomy is essentially an observational science where direct manipulation of celestial objects is impossible (except for moon rocks, meteorites and comet dust). Unlike physicists or chemists, who can isolate variables in an experimental set-up to study their effect on the whole system, astronomers can only observe electromagnetic waves (and, since recently, gravitational waves) emitted by celestial objects and try to extract from these signals as much information as possible about their origin, their nature, and their evolution.

As is the case with all scientific inquiry, raw observations collected by astronomers never directly answer their research question; the data must be analyzed to highlight correlations, cycles, systematicities and invariants hidden in the observations. It is the synthetic elements resulting from this analysis, and not the raw data themselves, that help astronomers figure out the mechanisms underlying the astronomical phenomenon they observed.

The result of this analysis will then lead astronomers to create a model, whether a concrete, physical model, a mathematical model, or as is increasingly the case in modern astrophysics, a numerical model. Through the model, which is a functional and simplified representation of a class of objects or phenomena (Giordan and de Vecchi, 1987; Roy and Hasni, 2014), astronomers retain only certain elements of a complex reality to create a simpler and more easily manipulatable representation. Since manipulating celestial objects is impossible, the model is also the only tool that can be used to control variables, test a new hypothesis, make predictions, etc. The model in astronomy thus has a dual epistemological status (Mathewson, 2005): it serves to reproduce observations (model-validation phase), but also to make predictions about other aspects of the system under study (model-application phase). For astronomers, the model is what the experimental setup is for the physicists or chemists.

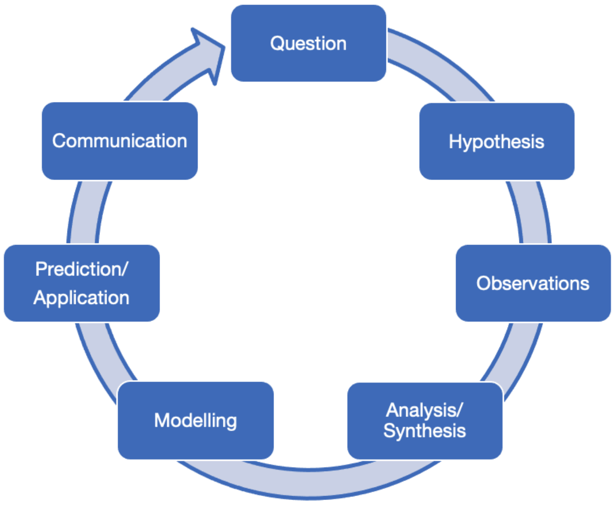


Figure 1. The astronomy knowledge-building cycle. Credit: Author

The results of this sequence of observation, analysis, and modelling, will then be used to make predictions and propose new applications of the model to other astronomical phenomena. Finally, the conclusions of the research will be communicated to the research community, mostly in the form of a scientific article, whose purpose is to share new results and ideas, but also to submit them to critical peer review. The communication will also raise new research questions and start a new cycle of observation, analysis, and modelling. It is the cyclical nature of astronomical research, grounded in the way scientists do empirical science, that we call the "astronomy knowledge-building cycle", shown in Figure 1.

Of course, Figure 1 shows a much-simplified vision of the process of knowledge-building in astronomy: in reality, there is always a back-and-forth between certain stages, for example between analysis, synthesis, and modelling, since one necessarily informs the other. Also, Figure 1 does not account for the many micro-decisions that must be made within each step, for example in the choice of one observation instrument over another. Finally, we know that the process of building new knowledge in science is anything but linear and that several trials, errors and backtracks mark its path (Fourez, 2001).

There are many historical examples to support this epistemological view of the construction of new knowledge in astronomy. The history of the Copernican revolution (Kuhn, 1957) is a classic illustration. In seeking to answer the question "what lies at the centre of the solar system?", Nicolaus Copernicus put forward the heliocentric hypothesis in 1543. From 1582 to 1600, Tycho Brahe conducted a series of observations of the planet Mars, producing exquisitely precise data that Johannes Kepler analyzed to build a mathematical model, the three laws of planetary motion, published in his Astronomia Nova (1609). Kepler then published the Rudolphine Tables (1627), a direct application of his model, based on elliptical orbits, which were the most accurate ephemeris published to date. The Tables also led to the prediction of solar transits by Mercury and Venus in 1631 and 1639 respectively, transits that were duly observed by several astronomers and thus confirmed Kepler's model (Athreya and Gingerich, 1996). Several new questions were raised by then about the structure, origin and evolution of the solar system, questions which started a flurry of new research cycles. Other examples, such as the discovery of Neptune (Grosser, 1962), the development of the Hertzsprung-Russell diagram (Porter, 2003), or, more recently, the discovery of extrasolar planets with the Kepler Space Telescope (Chastenay, 2020), all illustrate how astronomers produce new understanding through the knowledge-building cycle in astronomy.

We conclude from this section that as a tool to describe the production of knowledge in astronomy, the knowledge-building cycle in astronomy is sufficient to understand the work of scientific researchers in astronomy and to proceed to a didactic transposition in the classroom, as we will discuss in the next section.

3 Knowledge-Building Cycle, Scientific Inquiry, Didactic Transposition and Conceptual Change in Astronomy

Students walk into our classrooms carrying several conceptions (also labelled misconceptions, naïve conceptions, preconceptions, etc.) about natural phenomena, and the lunar phases are no exceptions. Chastenay and Riopel (2020, Appendix) have created a comprehensive list of the most common students' misconceptions about lunar phases, the most frequent being the shadow cast by Earth on our satellite. It is widely accepted that one of the goals of science teaching is conceptual change. According to Hewson (1992), "it is the teacher's responsibility to be aware of students' conceptions and to teach in ways that are likely to facilitate conceptual change on the part of the students." (p. 10) Dole and Sinatra (1998) add that conceptual change is most meaningful when it is intentional, that is, when learners are aware of the need to change, can clearly identify what needs to be changed (Luque, 2003), and are able to self-regulate the process of conceptual change (Jonassen, 2008). These abilities give the learners agency within the conceptual change process they are engaged in.

But to be willing to change their conceptions, learners must first realize that they hold personal, often unconscious, conceptions about the world (Thouin, 2017), and recognize that their initial ideas are more or less satisfactory for describing and explaining the phenomenon under study (Posner et al., 1982; Strike and Posner, 1985, 1992). Secondly, since conceptual change typically occurs at the interface between learners' initial conceptions and their experiences with the world (Vosniadou, 1992, 1994), one way to get learners to fully engage in the process of conceptual change is to provide them with experiences (in a larger sense) that may lead them to want to question and change their initial ideas.

In the context of teaching basic concepts in astronomy in elementary and high schools, we propose that such experiences, based on the astronomy knowledge-building cycle, will promote conceptual change among learners. By transposing the astronomy knowledge-building cycle in the science classroom, and presenting it as a process of scientific inquiry that includes observation, modelling and communication (Windschitl et al., 2008), we can establish functional links between the stages of the knowledge-building cycle in astronomy, the steps of scientific inquiry, the didactic objectives that follow once these steps are transposed into the classroom, and the process of conceptual change; we match these elements in Table 1 and detail them in the following paragraphs.

1. Question: the first step in any inquiry-based teaching is the research question, which stems from curiosity and that learners must take on to ensure the success of the learning process; this is what Brousseau (1986) called the process of problem devolution, through which learners make the research question their own and gain the motivation to invest in the search for an answer, even though at first, they do not possess all the conceptual tools necessary to succeed (Astolfi, 1994). Through problem devolution, the learning becomes intentional, one of the conditions for successful conceptual change (Dole and Sinatra, 1998).

2. Hypotheses: The second step of inquiry-based teaching, the expression of a variety of hypotheses in the classroom, reveals learners' personal explanations, their conceptions, which are often implicit and unconscious (Thouin, 2017). The variety of hypotheses and conceptions present in the classroom may bring learners to reconsider their own personal explanations, creating dissatisfaction with their conceptions through cognitive and socio-cognitive conflicts, which is an important step in the mechanism of conceptual change as proposed by Posner et al. (1982) and Strike and Posner (1985; 1992). These hypotheses will also be the basis for a discussion between peers about the observations needed to sort out hypotheses and answer the research question.

3. Observation: systematic observation of an astronomical phenomenon is essential to familiarize learners with its various aspects. Indeed, one cannot take for granted that learners are able, in the absence of prior systematic observations, to produce an accurate and complete description of the phenomenon under study. This familiarity is essential to provide students with the necessary experience with the phenomenon that will help them build up a bank of personal memories of what it looks like. But one must recognize that younger students might find it difficult to make systematic observations of astronomical objects. For instance, younger students might have difficulty simply drawing the aspect of the Moon in the sky. It is thus important to adjust what is to be recorded about observations and tailor it to the abilities of students.

According to Plummer (2012), learning to observe and record astronomical phenomena systematically improves learners' understanding of these phenomena. This amounts to increasing learners' intelligibility of the phenomenon, which is another step in the conceptual change process proposed by Posner et al. (1982) and Strike and Posner (1985; 1992). Moreover, in the case of astronomy, observations replace the experimental approach that is more common in inquiry-based teaching of other scientific concepts in schools.

4. Analysis/Synthesis: The subsequent analysis of the observations allows learners to extract from the sum of the raw data the essential elements that their model will then have to reproduce. But extracting patterns, cycles, invariants, and correlations from this abundance of data is difficult and, at this crucial stage, learners need help, in the form of scaffolding, to guide them in the analysis of their data (Bowen and Bartley, 2020). As with observations, this step further increases the intelligibility of the phenomenon under study by reducing the mass of data to a small number of synthetic "facts" that will have to be reproduced and explained by the model.

5. Modelling: The modelling stage is central to the success of the conceptual change process. According to Astolfi and Drouin (1992), modelling is a true "problem-solving tool" (p. 93), and it is at the modelling stage that learners truly construct their new understanding of the mechanism behind the phenomenon being studied. Jonassen (2008), and Lee, Jonassen and Teo (2011) suggest that model building is one of the most conceptually

Table 1. The knowledge-building cycle in astronomy, the steps of scientific inquiry, their didactic transposition in the classroom and their links to the process of conceptual change.

Knowledge-Building Cycle in Astronomy	Step of Scientific Inquiry	Didactic Transposition in the Classroom	Process of Conceptual Change
1. Question	Learners identify a problem/ask a question	Learners take charge of the question and the problem to be solved	Through devolution, learning becomes intentional
2. Hypotheses	Learners propose one or more hypotheses with a justification ("I think that… because…")	Learners express their initial conceptions and create (socio)cognitive conflicts in the classroom	Learners begin to feel dissatisfied with their own conceptions
3. Observation	Learners use different methods to collect systematic observations	Learners become familiar with the aspects of the astronomical phenomenon under study	Learners continue to feel dissatisfied with their own conceptions and begin to reconsider them, as they increase their familiarity with the phenomenon (intelligibility)
4. Analysis/Synthesis	Learners analyze their data, looking for cycles, correlations, etc.	Learners look for regularities in the data, create a common base of facts (synthesis) to be explained by future modelling (i.e. what is to be explained)	Learners continue to reconsider their conceptions and they increase their familiarity with the phenomenon (intelligibility)
5. Modelling	Learners learn what is a scientific model and use/create their own model to reproduce observations	Learners create models that are the visible manifestation of their evolving conceptions, making connections between observations, analysis, and modelling, and allowing perspective-taking on astronomical systems	Learners are familiar with the phenomenon, new conceptions appear plausible, modelling drives the evolution of conceptions
6. Prediction/Application	Learners use their models to make predictions and apply them to novel situations	Learners are motivated by the success of their models as they learn to decontextualize and recontextualize them	Learners demonstrate the success (fruitfulness) of their new conceptions
7. Communication	Learners communicate their models and their results to peers	Learners anchor the model in their own language, increasing their familiarity with the astronomical concept and its various aspects	Learners put new conceptions into words and form new concepts

engaging tasks students can undertake in the classroom: "when students construct models, they own the knowledge" (Jonassen, 2008, p.680). This step is also an opportunity for learners to become familiar with the modelling approach, which is often less used in schools than the experimental approach. Concrete, physical models, which younger learners can manipulate directly, are also most likely to help change their prior conceptions (Harrison and Treagust, 2000).

At first, the models constructed by learners will likely reflect their own conceptions, but these will have to evolve in response to the results of the analysis; ultimately, it is by comparing the model to the synthesis of observational data and adjusting it so that it better represents the observations, that the model (and students' conceptions) will evolve. The same thing happens when professional astronomers analyze their observations, identify patterns in the data, develop models that reproduce what they observed and, ultimately, use them to help explain and understand the universe (Plummer, 2017).

Building and using a model that dynamically and functionally represents an astronomical system also helps facilitate learners' development of an important spatial skill in astronomy, namely perspective-taking. According to Sadler (1992), "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, modelling allows one to shift perspective on astronomical systems, from the geocentric point of view (which is the one from which learners have been systematically observing and recording the phenomenon under study) to the "allocentric" point of view (i.e., the view from space, see Chastenay (2016)) which allows one to encompass an entire astronomical system. By switching from one perspective to the other, learners can relate the overall characteristics of the model to the aspect of the phenomenon as seen from Earth, as they observed it. Modelling and perspective-taking further allow learners to create their own mental model of the system under study. This mental model will help them represent the system as a whole, thus relieving working memory space and providing flexibility in manipulating the model and its constituents through "mental" perspective-taking, all without having to resort to the physical model itself (Nersessian, 2013).

6. Prediction/Application: predictions and applications, based on the model, are important sources of motivation that ultimately demonstrate the plausibility and fruitfulness of new conceptions associated with the model. Plausibility and fruitfulness are essential elements of the conceptual change model of Posner et al. (1982) and Strike and Posner (1985; 1992). What's more, the application of the model to similar, but different, situations than the one studied allows for new knowledge to be "decoupled" from the context in which it was constructed and applied in new contexts, a process of decontextualization and recontextualization that is a necessary condition for the development and broader application of abstract concepts (Vygotsky, 2014) and their possible transfer to diverse situations (Holbrook and Rannikmäe, 2010).

7. Communication: peer-to-peer communication is very important to properly anchor the model in the learner's conceptual network. As Vygotski wrote, "the word is the direct tool of concept formation" (2014, p. 525). For Paillé and Mucchielli, "the resources of language […] are the tools of representations" (2016, p. 37, free translation); words create an interface between concepts and empirical entities. It is often when students describe and explain their models that they fully form their ideas; anyone who has ever taught knows that it is when one must explain a concept that one truly understands it. Sherrod and Wilhelm's (2009) work on teaching lunar phases makes it clear that learners' classroom discourse provides an optimal setting for them to build their understanding of an astronomical phenomenon like the phases of the moon.

4 Doing Astronomy Like Astronomers Do: An Empirical Study

4.1 Research Objectives

Based on the theoretical concepts and practical considerations related to the process of conceptual change and the didactic transposition into the classroom of the knowledge-building cycle in astronomy, in the form of a scientific inquiry process including observation, modelling and communication, we designed a two-day professional development (PD) program aimed at in-service elementary and high school teachers (from 4th grade in elementary school to the first year in high school) to teach the phases of the Moon. We hoped that this PD program would achieve two main objectives: firstly, raise the knowledge base of in-service teachers about the lunar phases, and secondly, raise the perception of their own competence (self-efficacy) about teaching the lunar phases in their classroom. We also hoped that by participating in this PD program, teachers would be willing to test their new knowledge base and teaching skills right away with their students by using the same approach to teach them about lunar phases in the classroom. In other words, we hoped that by "Doing astronomy like astronomers do", in-service teachers would lead their students to study the lunar phases by using the same approach. Thus, the objectives of our study were twofold:

1. Evaluate the impact of the two-day PD program about lunar phases on the knowledge base and self-efficacy of in-service elementary and high school teachers.
2. Evaluate the impact of the two-day PD program about lunar phases on the knowledge base of students of in-service elementary and high school teachers engaged in the program.

4.2 Description of the PD Training Program

The whole PD training activity took place over two days separated by about a month and included the following stages:

Day 1: Presentation of the conceptual framework of the activity ("Doing astronomy like astronomers do"), including what is scientific inquiry (including observation, modelling, and communication), examples of the knowledge-building cycle in astronomy, how can it be transposed in the classroom, and the process of conceptual change, including common students' conceptions about the phases of the Moon (see Chastenay and Riopel (2020), Appendix). Presentation of the tools for observing the lunar phases over the following weeks (Lunar Phases Observation Log, see Figure 2; and the free astronomy software Stellarium© `https://www.stellarium.org`) and how to use them. Definition of "elongation" and "illumination" and presentation of a simple protractor tool to measure the elongation of the Moon (available from the author).

Day 2 (a month later): Review of the month-long observations of lunar phases, analysis of the Lunar Phases Observation Log using a worksheet provided by the author (scaffolding), concrete modelling in a darkened room, decontextualization and recontextualization (predictions and applications, for instance visibility of the Moon according to its phase, phases of the Earth as seen from the Moon, phases of Mercury and Venus, phases of Jupiter's satellites, etc.), open discussion on the conditions of application of this educational approach in elementary and high school science classrooms.

Between Day 1 and Day 2, over the course of one month, participants were asked to observe the Moon daily and complete their Lunar Phases Observation Log (Figure 2), either by direct observation or by using the free astronomy software Stellarium© or another astronomy app on their cellphone (Persson and Eriksson, 2016).

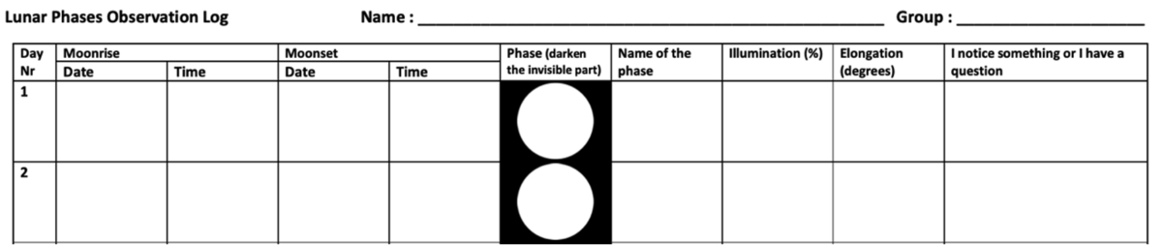
During Day 2, after a little more than a month of observations, the participants were asked to analyze the data collected using a worksheet prepared by the author. The worksheet, which provided a form of conceptual scaffolding in the analysis of the observation data, was used to guide teachers in the search for invariants, correlations and cycles embedded in their data. For example, teachers were led to realize that the Moon's terminator always moves from right to left across the lunar disc (Figure 3). By plotting graphs of the Moon's illumination and elongation as a function of its phase, participants were able to better appreciate the cyclical nature of lunar phases as well as the connection between the Moon's position in its orbit and its phase (Figure 4).

After they had completed the worksheet, participants were invited to fill a blank table (Table 2) to create a summary (synthesis) of their observations. It is this table, as well as other aspects of the lunar phases like those shown in Figures 3 and 4, that was to become the basis of the modelling process that followed.

Still on the second day, the results of this analysis were used as a basis for in-service teachers to explore, in dyads, various concrete models (for example, a white Styrofoam ball on a stick representing the Moon, a bare light bulb for the Sun and their own head representing the Earth, see Figure 5, or a plastic hula hoop held at eye level representing the plane of the Moon's orbit) to reproduce their observations. The teachers were invited to discuss among themselves and present their model to one another to allow for more dialogue. These models were used not only to replicate what had been observed over a month, but also to predict the next lunar phases, explain the variation of the moon's rising and setting times according to its phase (by including the Earth's daily rotation in the model), explore the formation and frequency of lunar and solar eclipses (with

Table 2. A summary of a month-long observation of lunar phases, to be filled by participants (in italics).

Phase	Rise	Set	In the Sky	Elongation (degrees)	Illumination (%)
New Moon	*Sunrise*	*Sunset*	*All Day (but invisible)*	*~ 0*	*0*
First Quarter	*Noon*	*Midnight*	*Afternoon & Evening*	*~ 90*	*50*
Full Moon	*Sunset*	*Sunrise*	*All Night*	*~ 180*	*100*
Last Quarter	*Midnight*	*Noon*	*After Midnight & Morning*	*~ 90*	*50*
Other facts about the lunar phases that I noticed...					
The Moon changes from day to day in a progressive and predictable way.					
The terminator moves across the lunar disc form right to left.					
The Moon rises and sets about an hour later each day.					
During a lunar cycle, the Moon is waning, then full, then waxing, then invisible (new moon).					
The angle between the Moon and the Sun (lunar elongation) increases when the Moon is waxing and decreases when the Moon is waning.					
The illumination of the Moon (% of the disc visible) increases when the Moon is waxing and decreases when the Moon is waning.					
We always see the same face of the Moon.					
...					



Lunar Phases Observation Log Name : ______ Group : ______

Day Nr	Moonrise Date	Moonrise Time	Moonset Date	Moonset Time	Phase (darken the invisible part)	Name of the phase	Illumination (%)	Elongation (degrees)	I notice something or I have a question
1									
2									

Figure 2. The Lunar Phases Observation Log (excerpt). Credit: Author.

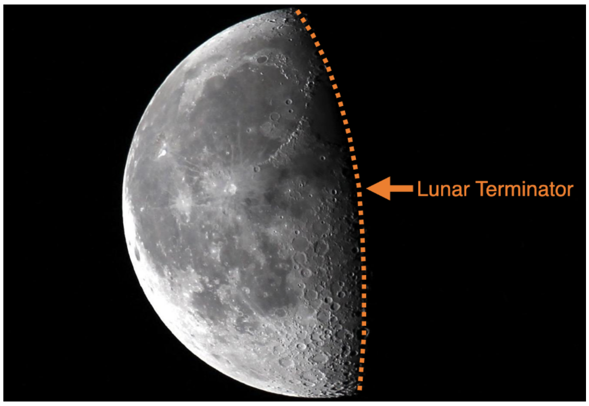


Figure 3. The lunar terminator is the dividing line between the illuminated and dark parts of the Moon's disc. In the Northern hemisphere, the terminator always travels across the Moon's disc from right to left (from left to right in the Southern hemisphere). Credit: Author and NASA.

a plastic hula hoop model), etc. Emerging questions were also investigated with the models, such as the formation of phases elsewhere in the solar system, i.e., the phases of the Earth as seen from the Moon, the phases of Mercury and Venus as seen from the Earth, the phases of the satellites of Jupiter and Mars, etc.

4.3 Teachers Teaching Students About the Lunar Phases

At the same time as in-service elementary and high school teachers participated in the PD program, three of them accepted to teach the lunar phases to their students using the same approach of "Doing astronomy like astronomers do". They explained the approach to their 5th and 6th grade (elementary, aged 10-12 years old) and first year of high school students (aged 12-13 years old, see Table 3, next section), discussed the research question, then they had students discuss ideas and hypotheses and implemented the same observing tools (Lunar Phases Observation Log, Stellarium©, etc.) before launching a month-long observation program. Each day at the start of class, or at the start of each science class in high school, a few minutes were set aside to discuss observations made previously, answer questions about the observation log and other observing tools, and discuss puzzling findings and realizations made by the students, for instance the fact that the Moon is visible in the daytime (the activity was launched around First Quarter, when the Moon

Table 3. Demographics of participant elementary and high school students.
†Secondary 1 is the first year of high school.

Teacher	School Grade	Mean Age *(SD)*	*N*	Teaching intervention
Ms. É. C.	5^{th}-6^{th}	11.4 *(0.5)*	21	Doing astronomy like astronomers do
Ms. J. R.	6^{th}	11.8 *(0.4)*	13	Doing astronomy like astronomers do
Ms. I. P.	Sec. 1†	13.1 *(0.3)*	27	Doing astronomy like astronomers do
Ms. I. P.	Sec. 1	13.1 *(0.3)*	27	Doing astronomy like astronomers do
Ms. I. P.	Sec. 1	13.2 *(0.3)*	26	Doing astronomy like astronomers do
Ms. C. L.	5^{th}	10.5 *(0.3)*	22	Textbook, exercise book and videos

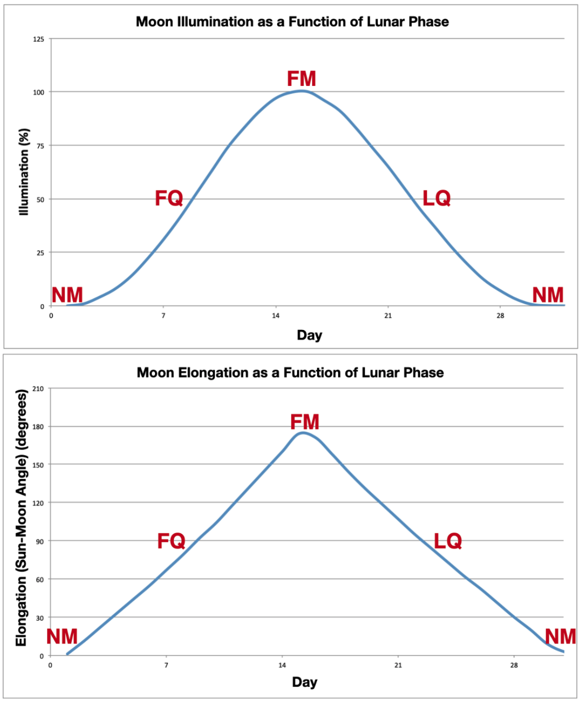


Figure 4. Illumination (top) and elongation (bottom) of the Moon according to its phase over one month (NM: New Moon; FQ: First Quarter; FM: Full Moon; LQ: Last Quarter). Credit: Author.

is visible in the afternoon and early evening), that it rises and sets about 50 minutes later each day, that the appearance of the Moon changes gradually as it waxes and wanes, etc.

At the end of the month-long observing campaign, students used the same tools as in-service teachers to analyze their observation log and modelled the lunar phases in their darkened classroom using the same props. All in all, students, like their teachers, studied the lunar phases by "Doing astronomy like astronomers do". The Appendix presents a detailed log of classroom activities conducted by these three teachers.

4.4 Participants

A total of 21 in-service elementary and high school teachers participated in the PD training program and 18 accepted to participate in the present study. The age range of participant teachers was 26 to 57 years old (M = 39,6, SD = 7,5) and their years of teaching experience in elementary and high school varied form 0 (first year of teaching not yet completed) to 28 years (M = 12,8, SD = 7,7). Table 3 presents the demographics of elementary and high school students who participated in the study. Ms. I. P. taught three classrooms in the first year of high school (Secondary 1) that all participated in the research. Table 3 also includes demographics of a control group, the 5th grade class of Ms. C. L., who did not participate in the PD training program and taught the lunar phases using a more "traditional" approach, with textbook, exercise book and watching online videos about the phases of the moon. The control group did not make observations nor modelling while studying the lunar phases over the course of one week. Unfortunately, it was not possible to form a control group of elementary and high school teachers to compare with those who participated in the PD program.

4.5 Instruments

In this study, we compared pre-post-intervention measurements to assess the impact of the PD activity on in-service teachers' astronomy learning about the phases of the Moon, as well as their self-efficacy teaching the lunar phases, defined as how they perceive their ability to understand and teach the lunar phases, compared to their peers, or to what their own perceived ability was at the beginning of the training (Bandura, 1977, 2000; Cokley, 2000). To conduct these assessments, we used the Moon Phases Concept Inventory for Middle School (MPCI-MS), a valid 19-question, multiple-choice questionnaire about the phases of the Moon (Chastenay and Riopel, 2020) as well as a self-efficacy questionnaire based on a valid instrument developed by Potvin and Hasni (2014). The latter is a six-level Likert scale questionnaire asking respondents to indicate their level of agreement or disagreement with statements such as "Compared to other teachers participating in the PD training, I consider myself good at teaching the phases of the Moon." The Cronbach's alpha of the self-efficacy questionnaire, calculated from participants' responses, is .886 (pretest) and .718 (post-test), which is generally considered very good and good, respectively (Cronbach, 1949, 1951).

The same Moon phases concept inventory was used with elementary and high school students to measure their learning gains about the lunar phases before and after the teaching intervention by their teachers. We were also able to return to the two elementary classrooms two months after the end of the intervention to administer the concept inventory one last time, to assess long-term retention (it was not possible to repeat the delayed measurement in the three Secondary 1 classrooms due to a tight teaching schedule). All test score distributions were normal (nonsignificant Shapiro-Wilk tests) and we were able to compare the pretest and post-test means for each measurement using a series of T-test for paired-sample. Results are presented in the next section.

4.6 Results

Both instruments were administered before the training activity began and again at the end, both for in-service teachers and their students (and again two months later for elementary students). For in-service teachers, results of two T-tests for paired samples show a statistically significant increase in knowledge about the lunar phases (Mean Score Pretest = 20.000 [1], Mean Score Post-test = 27.611, Mean Difference = 7.611, SD = 3.616, $t(17)$ = 8.930, p < .001, d = 2.10), as well as for their own perceived self-efficacy in understanding this topic and teaching it to their students (Mean Score Pretest = 4.019, Mean Score Post-test = 5.483, Mean Difference = 1.464, SD = 1.067, $t(17)$ = 5.820, p < .001, d = 1.37). Cohen's d, a measure of the difference between the means of the post-test and the pretest in terms of SD (Cohen, 1988; 1992), show a huge intervention effect for teachers learning about moon phases (d = 2.10), as well as a very large effect on their self-efficacy (d = 1.37, see Sawilowsky (2009)). The three teachers who participated in the PD training and taught their students the lunar phases according to the same approach had similar individual results. Table 4 presents the results for participating students, experimental and control groups. Since both experimental groups at the elementary level had the same characteristics and similar results, they were com-

1 Even though the MPCI-MS is a 19-question instruments, several questions contain sub-sections that lead to more than one response, hence the maximum score for the questionnaire is 30.

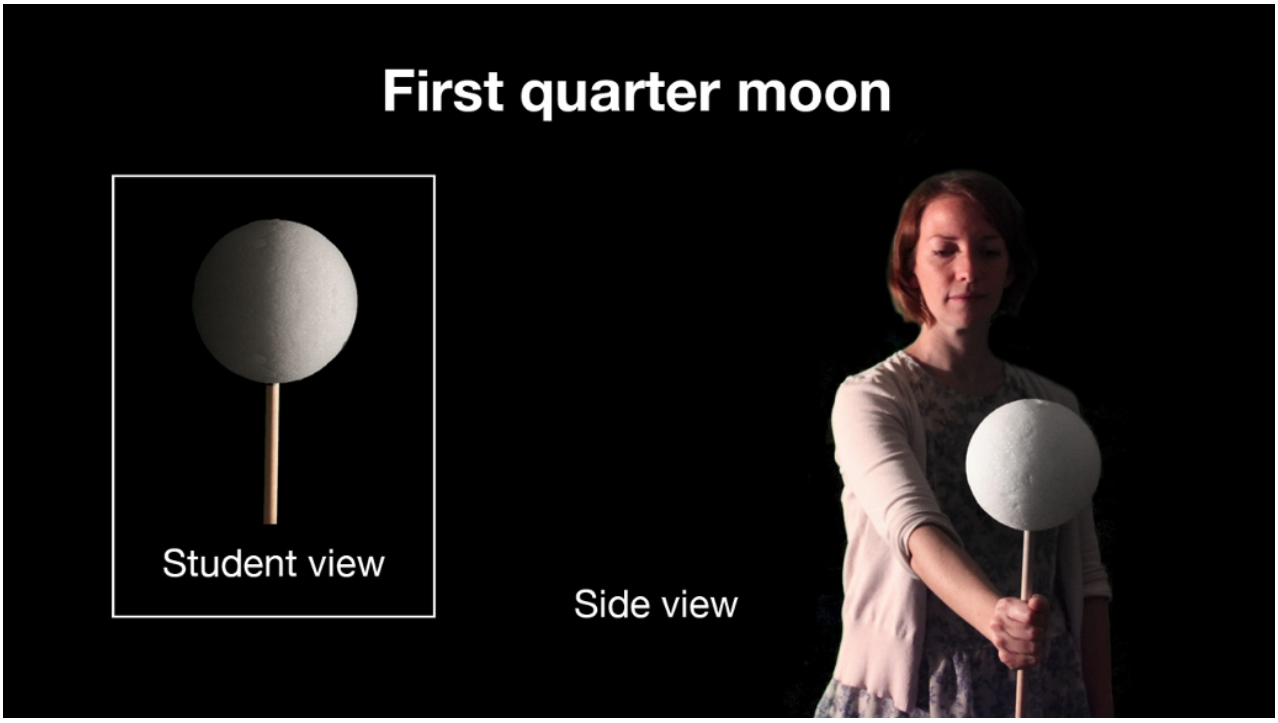


Figure 5. Modelling the phases of the Moon using a concrete model. In this image, a lamp representing the Sun is located on the left (out of the picture's frame). The key to the success of this activity is a perfectly dark room, ideally without windows, to eliminate stray light. Credit: NASA.

Table 4. Results of T-tests for paired samples comparing students' Moon phases concept inventory mean score differences between pretest, post-test, and delayed post-test (2 months later, elementary experimental group only).
†Ten students in the three Secondary 1 experimental classrooms could not complete the post-test and were excluded from the analysis.

Group	N	Moon Phases Concept Inventory	Score Pre	Score Post	Mean diff.	*SD*	*t*	*p*	Cohen's d
Elementary Control	22	Post-Pre	13.864	14.730	0.864	3.603	1.124	.274	0.24
Elementary Experimental	34	Post-Pre	13.353	21.529	8.176	3.988	11.954	.001	2.05
Elementary Experimental	34	Delayed Post-Pre	13.353	19.706	6.353	4.007	9.245	.001	1.59
Elementary Experimental	34	Delayed Post-Post	21.529	19.706	-1.823	2.139	-4.972	.001	0.85
Secondary 1 Experimental	70†	Post-Pre	15.045	20.478	5.815	4.512	10.782	.001	1.29

bined for this analysis; we proceeded the same way for the three Secondary 1 classrooms.

Results for elementary students in the control group show that the "traditional" teaching intervention did not produce a significant difference in terms of students learning about the lunar phases. On the contrary, for the experimental groups, the teaching intervention based on "Doing astronomy like astronomers do" produced significant learning gains. In the elementary classrooms, these gains decreased slightly after two months, but were still significantly larger than the pretest results. Cohen's *d* for the experimental groups shows a huge effect of the intervention in the elementary classrooms (d = 2.05) that decreases to a very large effect after two months (d = 1.59), and a very large effect in the three Secondary 1 classrooms (d = 1.29), whereas the effect of a traditional teaching intervention is small for the control group (d = 0.24).

5 Discussion and Conclusion

We have presented the epistemological and historical foundations of an approach to astronomy teaching, "Doing astronomy like astronomers do", based on inquiry-based teaching and aiming at fostering conceptual change among learners through the didactic transposition in the science classroom of the knowledge-building cycle in astronomy, in the form of a scientific inquiry including observation, modelling and communication. We tested this approach in the context of a two-day PD training activity for in-service teachers about the lunar phases, and in five classrooms from 5th grade to Secondary 1 taught by three teachers participating in the PD training. The results of an empirical study conducted with in-service teachers and their students show huge to very large gains in terms of learning about the phases of the moon, as well as very large gain in terms of the teachers' self-efficacy regarding their own understanding of the phenomenon and their sense of competence in teaching it. We also measured significant, and huge to very large knowledge gains about lunar phases with participant students, whereas a control group that studied the phases of the Moon using a more traditional approach showed no significant difference in knowledge gain between pretest and post-test, with a small effect of the teaching intervention.

These results are congruent with Plummer and Tanis Ozcelik (2015) findings, suggesting that teachers can develop coherent scientific inquiry investigations when support is given for them to understand the process of scientific inquiry and to gain relevant science content knowledge. Also, the opportunity that some of our participants had to apply directly in their classroom the teaching strategies developed in the PD training helped them gain confidence in their own teaching skills. This approach also allowed participant teachers to become aware of the richness of the process of scientific inquiry, which is not limited to experimental sciences, but can also include observation and modelling (Windschitl et al., 2008). In the case of scientific inquiry in astronomy, where the experimentation phase is replaced by systematic observation and modelling, teachers realized that the process of scientific inquiry is not a series of steps to be followed blindly, but rather a flexible, adaptable, and extremely rigorous approach that leads to real learning in school science. All this points to the importance of allowing in-service teachers, as well as preservice teachers, the opportunity to experience first-hand the process of scientific inquiry, as is promoted by curricula around the world, to develop the knowledge base and skills they need to be able to transpose this approach in their own classroom.

Table 4 shows a large difference between the pre-post-test knowledge gains of elementary students in the experimental group (d = 2.05) and that of Secondary 1 students (d = 1.29). In terms or maturation, one could have expected older students to do better than younger ones, which is not the case here. In conversations with the three teachers who taught these classrooms, we realized that the daily schedule arrangement in high schools, where Ms. I. P. would see her students only twice or three times a week for about 90 minutes each time, was less conducive to students' motivation and engagement in the process of observing the Moon on a daily basis, and noting their observations, whereas in elementary classrooms, time could be set aside every day to discuss previous observations, answer questions, etc. According to their teachers, elementary students were very involved in the process, and their teachers report that their motivation and engagement grew over one month, whereas the reverse effect was observed in the three Secondary 1 classrooms. This result illustrates the need for close monitoring of students, ideally daily, to sustain their interest and commitment in observing the phases of the Moon regularly and recording their observations in a systematic manner. Since in an inquiry-based approach to teaching astronomy, the observation log is a crucial link between hypotheses and models, through analysis and synthesis, it is key to the success of the whole enterprise and, as such, should be the main focus of teachers to motivate their students to look at the Moon every day.

One could argue that the simple fact that teaching the lunar phases by "Doing astronomy like astronomers do" takes much longer than teaching the phases of the Moon by using a textbook, videos, and a more traditional approach, is responsible for most of the difference in learning when comparing experimental students with those in the control group. It is true that the experimental approach presented here is a more time-consuming, more intensive activity (see Appendix) than simply reading a textbook, watching a few videos, and listening to the teacher. But it is also true that the result is a much better understanding of the concept and mechanism of lunar phases within the experimental group of students than with students of the control group.

Phases of the Moon is one of the most difficult astronomical topics to learn (Kavanagh et al., 2005), only slightly less difficult than learning the seasons (Plummer, 2012), and several studies have already shown the superiority of a model-based approach to teaching this topic, compared to traditional teaching. It might be that, if our goal is deep understanding on the part of our students of the mechanism behind such astronomical topics as diurnal cycle, phases of the Moon and seasons, instead of rote learning, then spending more time on a difficult concept is the only option. It is also important to keep in mind that by "Doing astronomy like astronomers do", students are not only learning an important lesson in astronomy, but they also get to experience how science is made and gain a deeper understanding of the way scientists work, by following an inquiry-based approach to study the lunar phases themselves.

As we have seen, we use the comparison between results from the post-test for the experimental and control groups to conclude that "Doing astronomy like astronomers do" is a better way to teach this difficult astronomical topic than a traditional, textbook-based approach. However, we don't know whether it is "behaving like an astronomer" that is the important factor at play here, or whether it is because the activity requires students to combine both hands-on (doing practical activities) and minds-on (really thinking about the concepts over a long period of time) learning. Surely, future studies should try to distinguish between these two factors that might influence learning.

We believe that our teaching strategy of "Doing astronomy like astronomers do" constitutes a promising approach that allows teachers to address a host of basic astronomical concepts in the classroom, such as the diurnal cycle, the seasons, the apparent motion of planets, etc., by leading students to observe phenomena systematically, to analyze their observations and to create models, in short, to do astronomy the way astronomers do. For example, using a gnomon or a simple sundial to systematically observe the daily apparent motion of the Sun across the sky would allow younger students to become fully aware, perhaps for the first time, of the details of diurnal motion (Plummer and Maynard, 2014), before modelling it in a concrete way by mimicking the motion of the Earth's rotation around its axis. It would also be an ideal way to allow younger students to develop the skills needed to record their observations in a meaningful way. In the study of the Earth's seasons, systematic observation of the times and positions of sunrise and sunset on the horizon at various times of the year, coupled with the height of the Sun at noon, would pave the way for modelling seasons with a globe that mimics the tilt of the Earth's rotation axis (Chastenay, 2023, accepted). In this case, as in the study of apparent planetary motions (the retrograde motion of Mars, for example), the use of astronomy software such as Stellarium© saves valuable time for the observation of astronomical phenomena that take place over long periods of time or are difficult for students to observe late at night, for example (Persson and Eriksson, 2016).

Asking questions, creating hypotheses, observing, analyzing, and synthesizing data, modelling, making predictions and communicating their results are central to the work of astronomers when building new knowledge, as it is for all scientists conducting empirical research. This work can be transposed in the science classroom, in the form of a scientific inquiry process that includes observation, modelling, and communication, to foster conceptual change and to help in-service teachers, preservice teachers, and their students learn basic astronomical concepts by "Doing astronomy like astronomers do".

6 Declarations

6.1 Ethical Considerations

This research was approved by the Centre interinstitutionnel d'éthique de la recherche avec des êtres humains (CIEREH) at Université du Québec à Montréal (certificate nr. CCER-16-17-23).

6.2 Consent for Publication

Not applicable.

6.3 Competing Interests

The authors declare that they have no competing interests.

6.4 Funding

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6.5 Author contributions

Chastenay: Conceptualization, data collection and curation, formal analysis, investigation, methodology, project administration, visualization, writing – original draft and revised version. Cormier, Lachance, Perez and Richard: Data collection. Richer: PD days organization and funding, data collection.

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8 Appendix

8.1 Doing Astronomy Like Astronomers Do—Classroom Activities Log

This log is based on daily journals kept by the participating teachers in the activity. Not mentioned in this list are moments when the MPCI-MS was administered in their classroom.

Week	Day	Description	Duration (minutes)
1	1	What do you know about the Moon? Elicitation of students' ideas about the Moon and its phases, drawing of concept map (optional).	30
	1	Predicting the order of lunar phases: Eight cut-out Moon phases to be placed in order according to students' ideas about future lunar phases, with the name of the phases they know. Students must also write their hypothesis: "I think the Moon shows phases because…"	20
	2	Weather permitting, observation of the First Quarter Moon in the sky (during recess, for example), elongation measurement with a Moon protractor (optional).	30
	2	Observing and noting the phases of the Moon with the Lunar Phases Observation Log: Presentation of the instrument, definition of new terms (illumination, elongation), presentation of Stellarium, how to fill each line of the Observation Log daily, comparison of Moon observations made earlier in the day with data from Stellarium.	90 to 120
	3-7	Observing the phase of the Moon each day. Weather permitting, students are encouraged to look for the Moon in the sky, draw the Moon or take photos and compare with Stellarium data.	10 to 15/day
2	1-7	Observing the phase of the Moon each day. Weather permitting, students are encouraged to look for the Moon in the sky, draw the Moon or take photos and compare with Stellarium data.	10 to 15/day
3	1-7	Observing the phase of the Moon each day. Weather permitting, students are encouraged to look for the Moon in the sky, draw the Moon or take photos and compare with Stellarium data.	10 to 15/day
4	1-7	Observing the phase of the Moon each day. Weather permitting, students are encouraged to look for the Moon in the sky, draw the Moon or take photos and compare with Stellarium data.	10 to 15/day
5	1-3	Observing the phase of the Moon each day: Last observations should overlap with first observations (i.e. same phase observed twice one month apart).	10 to 15/day
5	4	Analysing/synthesizing the Lunar Phases Observation Log: Students work in pairs to answer a series of questions about the data collected over one month with the Lunar Phases Observation Log. They fill a synthesis table at the end.	60 to 90
5	5	Modelling phases of the Moon: Students work in pairs in a darkened room to model the lunar phases with simple, concrete materials (Styrofoam balls, light bulb, hula hoop, etc.). For revision, teacher asks students to position the Moon to reproduce certain phases ("Simon says…"). Exploration of eclipses and phases elsewhere in the solar system. Students present their models to the rest of the classroom and discuss their findings.	90 to 120
6	1	Revising the order of lunar phases: Eight cut-out Moon phases to be placed in order according to students' ideas about future lunar phases, with the name of the phases they know. Students must write their (new) hypothesis "I think the Moon shows phases because…", comparison with prediction made during week 1.	20
6	1	Students are encouraged to share what they know about the lunar phases with students in other classrooms, with their parents and family, create video animations (with Scratch©), etc.	60