

Children Explaining Celestial Motion: Development of a Learning Progression

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Abstract

Extensive research has shown that students' understanding of astronomy does not resemble the scientific view. This study builds on our previous research in the area of *apparent* celestial motion to examine how children develop an understanding of the connection between the apparent motions of the sun, moon and the stars in the sky and the explanation for these motions, using the earth's rotation and revolution. Pre and post interviews were used to assess changes in student understanding following instruction designed to present apparent celestial motion through computer simulations followed by modeling of the explanations. Significant improvement was found across most areas among the third grade subjects (N=16). The main goal of this study was to begin the development of a learning progression for celestial motion and to test the use of this progression against the results of this instruction. The learning progression was created, through analysis of the domain, close examination of research on children's understanding, and the range of ideas expressed by students in this study. The progression was also found to be a useful scale, demonstrating the success of the instruction and providing insights for how future instruction may be improved to address students' alternative conceptions.

Key words: learning progressions; astronomy; elementary; observations; modeling

Introduction

The basis for understanding many aspects of astronomy is the ability to use the actual motions and relative positions of celestial objects (e.g. the sun and moon) to describe observed phenomenon and make predictions about the future. The National Science Education Standards recommend that students learn that “objects in the solar system are in regular and predictable motion” in 5th through 8th grades (NRC, 1996). Prior to this, NSES recommend that students learn the observable patterns of motion of the sun, moon and stars. The Benchmarks for Science Literacy (AAAS, 1993) recommend that between 3rd and 5th grades students learn that the “rotation of the earth on its axis every 24 hours process the night-and-day cycle. To people on earth, this turning of the planet makes it seem as though the sun, moon, planets and stars are orbiting the earth once a day.” An understanding of celestial motion is necessary for other standard topics of astronomy such as the phases of the moon and the seasons. And beyond this, a central way that astronomers (and scientists in general) make sense of the world is by looking for explanatory models to explain their human-centric observations. In this paper we focus on one aspect of this targeting how children learn to shift from their own perspectives to a looking down on the sun-earth-moon system perspective.

Without targeted instruction, most children and adults will not reach a scientific level of accuracy in their descriptions of the apparent motion of the sun, moon and stars from an earth based perspective (e.g. Baxter, 1989; Mant & Summers, 1993; Plummer, in press; Plummer, Zahm, & Rice, 2009; Sharp, 1996). Vosniadou and Brewer’s (1994) study of elementary children’s mental models of the day/night cycle and suggests that students may begin with naïve but logically consistent and empirically accurate models and that their descriptions and explanations may become less consistent as they attempt to assimilate scientific concepts into their prior framework. Prior research has established that first and second grade students are capable of improving their descriptions of the apparent motion of the sun and moon through instruction in the planetarium to a level more advanced than most middle school students (Plummer, 2009). Other studies have shown that upper elementary children can learn the scientific descriptions of the shape of the earth and the day-night cycle through the use of models (Diakodoy & Kendeou, 2001). Recent studies have also shown that children can learn how to explain the phases of the moon through inquiry and modeling as young as 2nd – 4th grade (Hobson, Trundle, & Sackes, 2009; Trundle, Atwood, & Christopher, 2007). Currently, few studies directly examine the connections between how children describe apparent celestial motion and the explanations for this motion or the impact of instructional interventions on the full celestial system included in celestial motion (earth, sun, moon and stars).

In this paper we will begin by reviewing the relevant literature which situates this work in past studies of children’s understanding of the shape of the earth, the earth’s rotation, and the moon’s orbit. We will then explain theoretical perspective we take, focusing on the creation of *learning progressions* and the prior research supporting our instructional intervention. Our goal is to demonstrate how an analysis of the discipline (astronomy) combined with knowledge of children’s ideas and development through targeted instruction can be used to develop a learning

progression which can help future curriculum developers and assessors in the area of celestial motion.

Shape of the Earth

The greatest effort in research related to astronomy education appears in the area of children's initial understanding of the shape of the earth and gravity. Children's initial ideas have been assessed across age groups and across cultures. Children's initial understanding of the world is based on their personal interactions and observations leading to a general understanding that the earth is flat and unsupported objects fall down (Vosniadou & Brewer, 1992). As children are exposed to scientific concepts through cultural and school interactions, they find ways to incorporate the scientific concepts into their naïve framework (Nussbaum & Novak, 1976; Nussbaum & Sharoni-Dagan, 1983; Vosniadou & Brewer, 1992). For most children the result is a synthetic model of the world that combines features of their observations and the scientific description of the world. Interviews with students across elementary grade levels have led to a general categorization earth shape and gravity notions that supports the conclusion that there is a developmental progression from naïve to synthetic or scientific understandings, though not all students will reach that scientific understanding (Nusbaum & Novak, 1976; Nussbaum & Sharoni-Dagan 1983; Samarapungavan, Vosniadou, & Brewer, 1996; Vosniadou & Brewer, 1992). Vosniadou and Brewer give the following list of earth-shape notions (p. 549): sphere, flattened sphere, hollow sphere, disc earth, and rectangular earth.

Students also hold a range of gravity concept notions, with respect to their understanding of the earth. These range from the scientific description to initial ideas based on their experiences (Sneider & Pulos, 1983): gravity pulls objects to the center of the earth, gravity pulls objects on the surface of the earth towards the center (but outside of the earth there is a universal down), and gravity pulls "down" everywhere (thus people would fall off of the "bottom" of the earth). Students begin school with the initial naïve notion or possibly one of the ego-centric synthetic notions. But even by middle school, many students will not have attained the full scientific understanding of both earth shape and gravity (Nussbaum, 1979; Sneider & Pulos, 1983).

Rotation of the earth

A major pre-requisite towards understanding the earth's rotation is appreciating that the earth is an unsupported sphere. If children do not hold at least the notion that the earth is a spherical, unsupported body, they are likely to find it difficult to construct the scientific mental model of a rotating planet to describe the apparent motion of the sun, moon and stars. However, further studies are needed to determine the actual interaction children's knowledge of the shape of the earth and the rotation concept through studies that investigate instruction at early grades.

Research on children's explanations for why we have day and night may shed light on how children develop the concept of the earth's rotation, as well as that their alternative conceptions will present, as they learn to explain apparent celestial motions. As with the earth shape and gravity notions, children's early explanations for the day-night cycle are primarily naïve and are based on observations of the world.

Most young children begin schooling with the belief that the earth is a physical object and the sun, moon, and stars are astronomical objects. Children's understanding of the day-night phenomenon, as well as the movement of these objects, are constrained by children's beliefs about physical objects that arise from aspects of naïve physics (Diakidoy, Vosniadou, & Hawks, 1997; Samarapungavan, Vosniadou, & Brewer, 1996; Spelke, 1991; Vosniadou & Brewer, 1994).

The prevalent notion that frames most children's naïve explanations are based on two general presuppositions: that the sun (and sometimes moon) are occluded resulting in night time darkness or that the sun moves straight up and straight down (Plummer, in press; Samarapungavan, Vosniadou, & Brewer, 1996; Vosniadou & Brewer, 1994). In addition to these ideas, 6 of the 12 Mexican-American children in Klein's study (1982) gave responses that indicated the sun is not an inanimate object. Klein reports that the students described the sun as "hiding behind the mountains," "hiding behind the clouds" or "hiding behind trees" at night, which the author suggested was evidence of precausal thinking (p. 105). Animistic models have also been found among Native American (Lakota/Dakota) children who suggested that "the sun and moon want to rest", "the sun is scared" at night, or referred to Lakota mythology (Diakidoy et al., 1997, p. 176).

The second order constraints on children's understanding of celestial motion arise from how children understand the physical properties of celestial objects (Samarapungavan, Vosniadou, & Brewer, 1996; Vosniadou & Brewer 1994). Studies using interviewing techniques that include having children draw their ideas (American children; Vosniadou & Brewer, 1994) and use physical models (Indian children; Samarapungavan et al., 1996) have found a developmental progression of children's ideas, with older students moving towards more heliocentric explanations for the day-night cycle. Some of this development appears to be linked to the development of the spherical earth model. Vosniadou & Brewer (1994) hypothesized that children must hold a spherical earth model in order to use the earth's rotation about its axis to explain the day-night cycle. Samarapungavan et al. (1996) confirmed this prediction with their study of first and third grade children in India; children who held naïve or synthetic notions of the earth's shape did not use its rotation to account for the change from day to night.

In recent years, studies of children learning the concept of the earth's rotation have covered ages 9 through 12, though little research has been done with children at younger grades. Diakidoy and Kendeou (2001) compared two types of instruction on the day/night cycle and shape of the earth with fifth grade students (average age 10 years 5 months) in Cyprus. One type of instruction followed a standard, textbook-based curriculum. The second was designed to consider students prior knowledge and used interactive models to help students focus on explanations for the scientific phenomena. Students in the condition that was designed to facilitate conceptual change by considering their possible misconceptions showed significant improvement in understanding, at both an immediate post-test and a delayed post-test, over the students receiving text-based instruction. However, the results do not detail the nature of the change in understanding – it is not clear if students in one, both or neither improved specifically on the earth rotation concept (specifically tested on two out of 14 multiple choice questions).

In a study of Year 5 and 6 children in England (ages 9-11), Sharp and Kuerbis (2005) used a quasi-experimental design to investigate the use of an astronomy intervention on the topic of the solar system, including a lesson on the day/night cycle. This lesson allowed the students to observe the rising and setting positions of the sun, follow the shadow of the sun throughout a day, and use a globe and overhead projector to explain why the sun appears to move. As with Dikodoy and Kendeou's study (2001), instruction involved physical models and considered children's prior experiences. Students showed significant improvement in their scientific conceptualization after instruction, improving from 35.5% in the pre-test to 77.4% in the post-test and 74.2% in the delayed post-test. A third study of twenty-seven 12 and 13-year-old Greek children learning about celestial motion found that all students understood the scientific model of the day-night cycle of rotation after experiencing a virtual computer environment where students could manipulate three-dimensional representations of the actual celestial objects to learn the concepts (however, the study did not include a pre-assessment on their understanding) (Bakas & Mikropoulos, 2003).

Teaching the concept that the earth rotates is not enough to allow students to make the full connection between the earth's rotation and the apparent daily motion of the sun, moon and stars. In a study of English Year 7 and 8 students, after spending 11 1-hour lessons focused on mental model building in astronomy (covering concepts of motion in the solar system and explanations of the phases of the moon and seasons), few (38%, up from 22%) understood that the "moon is in the day-time sky as often as it is in the night-time sky" though they made great improvements in understanding the full celestial motion description of the moon orbiting the earth which orbits the sun (increasing from 48% to 90%) (Taylor, Barker, & Jones, 2003, p. 1120). Students learning to correctly transfer their understanding of the earth's rotation to the apparent motion of stars also appear to be difficult for students. Diakidoy and Kendeou (2001) found that despite learning to explain the day/night cycle, 31% of the fifth grade students did not transfer this concept to infer that the stars remain in the sky during the day. Dove (2002) analyzed 12-year-old English students' responses to a question that asked them to explain why the bright star Regulus appears to move across the sky. Most students (78%) correctly indicated that the apparent movement is because of the earth's rotation and most also stated (73%) that the motion is east to west. However, the remaining portion of students could not accurately describe how and why this motion occurs (and it would be interesting to test these students without presuming they know that the stars appear to move across the sky).

The orbit of the moon

The rotation of the earth allows us to begin to explain the apparent rising and setting of the moon in the sky. Understanding the earth's rotation in conjunction with the moon's 28-day orbit around the earth is necessary for explaining the phases of the moon: a pattern of changing appearance of the moon over that same 28 day cycle. Research on children's ideas about the moon reveals both misconceptions about the moon's actual movement and that this motion is not used to explain patterns of apparent motion by children. In a study of American students, Vosniadou and Brewer (1994) found that some believe that the moon and sun are fixed on opposite sides of the earth, with the earth spinning between them for day and night (5 of 20 third grade

students and 5 of 20 fifth grade students). Other students believed that the moon goes around the earth (4 students in third grade and 2 students in fifth grade) but the reason for this movement is to make night. Sharp (1996) found similar notions about 10- and 11-year old English children by examining the mental models they hold about the actual motion of the sun, moon and earth. Seventeen of forty-two students knew that the moon orbits the earth slowly and another one student believed that the moon orbits once per 24 hours. The remaining 22 students either believed that the moon is fixed in place (16) or were categorized as unsure (6). Of the 102 Greek 11-13 year olds in Bakas & Mikropoulos's study (2003), 76% knew that the moon orbits the earth. The remaining students either believed that the moon is stationary, moves in and out, orbits the sun along with the earth, or were unsure.

And among the students who may be aware of the actual motion of the orbiting moon, many if not most do not know how to use this motion to explain the apparent changes to the moon's appearance or patterns of motion. Several studies have shown that children through adults cannot explain why we have phases of the moon (Abell, Martini, & George, 2001; Barnett & Moran, 2002; Baxter, 1989; Sharp, 1996; Stahly, Krockover, & Shepardson, 1999; Trundle, Atwood & Christopher, 2002). And while the explanations for the daily change in the moon's rise and set time has not been explored among students, it is reasonable to assume based on other studies that show children have limited knowledge of the basic patterns of celestial motion that children are even less scientific in their use of the moon's orbit in connection with changes in the apparent pattern of motion (Plummer, in press).

Theoretical Framework

Learning progression framework

In this paper, we begin to elaborate a learning progression for the conceptual area of celestial motion. This work builds on our previous work to elaborate how children may progress in their understanding of the apparent patterns of celestial motion observable from an earth-based perspective without delving into how children may develop the explanations for those observations (Plummer & Krajcik, 2008). Our work here is preliminary as we have only a small population from which to draw and test our ideas though we are also drawing heavily from our knowledge of the discipline and the literature.

Given that there is limited time to devote to any one area of science in K-8 school time, it is necessary to determine which "big ideas" will give students the necessary foundational knowledge to understand their world and continue their education (NRC, 2007). Big ideas hold broad explanatory power in the domain, make connections across isolated concepts, and are developed over time as learners understand them in increasingly sophisticated ways (Anderson, 2008; Catley, Lehrer, & Reiser, 2005; Duschl, Schweingruber, & Shouse, 2007; Smith, Wiser, Anderson, & Krajcik, 2006). Designing science instruction around big ideas will help us weed out peripheral ideas and instruction that focuses on the rote memorization of disconnected facts. While the field is at the beginning of identifying what constitutes a "big idea" in each discipline, we argue that one big idea in astronomy is that observable phenomenon can be explained through the unobservable motions of the earth and moon (Plummer & Krajcik, 2008). Understanding of this big idea includes

the ability to explain the apparent daily motion of the sun, moon and stars, explain how the seasonal change of the sun's path leads to an explanation for the seasons, and explain how the motion of the earth and moon relates to the phases of the moon.

A learning progression describes how students' initial ideas entering school can be built upon through instruction to reach a level of understanding that aligns with scientific views of the motions and properties of celestial bodies. According to Smith et al., learning progressions "describe successively more sophisticated ways of reasoning within a content domain" (2006, p. 3) and can be used to suggest how students may build upon their knowledge towards an expert understanding. The development of this progression follows the framework used to develop learning progressions on the atomic-molecular theory (Smith, Wisner, Anderson & Krajcik, 2004), evolution (Catley, Lehrer, & Reiser, 2004), environmental literacy (Anderson, 2008) and as outlined in *Taking Science to School* (Duschl et al., 2007). It is important to note that moving along a learning progression is not inevitable. Rather the learning progression is a possible description of how students may progress with good instruction.

Even though this proposed learning progression for celestial motion builds on our research and evidence from the literature about children's thinking, it is still only a *possible* description of how a learner may move through the successively more complex ways of thinking about these concepts (Smith et al., 2006). Anderson (2008) refers to this as the learning progression hypothesis – "although the development of scientific knowledge is culturally embedded and not developmentally inevitable, there are patterns in the development of students' knowledge and practice that are both conceptually coherent and empirically verifiable" (p. 11). Not all students will move through this progression in the same order, nor will they all achieve the scientific understanding. There remain considerable gaps in our understanding of how children actually progress in their understanding of celestial motion, especially in terms of the effect of instruction on these topics. Therefore, due to the lack of longitudinal studies of how children's ideas change over time when exposed to good instructional materials and methods, this learning progression is a preliminary look at an area that should be investigated in significantly more depth.

Instructional intervention framework

A major piece of learning progression work is to identify instructional practices that will move students along a theoretical progression. Thus part of our work was to test a small instructional intervention's usefulness in this domain. We considered several theoretical perspectives relating to how students learn particular to this domain as we designed our instruction. As our previous literature review indicates, students lack an understanding of the earth-based perspective from which to develop explanations. To fully understand, children need to have an evidence based perspective to explain (Plummer, in press, 2009; NRC, 1996). In this way we grounded our instruction in an inquiry-based model (though did not follow through on the full enactment of an inquiry investigation). Developing children's understanding of apparent celestial motion requires that students acquire a repertoire of mental images that they can run through to model the daily motion of these objects. Prior research has found that children interacting with 3D planetarium-dome simulations (Plummer, 2009) and 2D personal computer based simulations (Bell & Trundle, 2008;

Hobson, Trundle, & Sackes, 2009) have been successful in promoting understanding of observational astronomy topics. This supports our assertion that observations of the real sky will rarely be enough (unless extensive time and scaffolding is provided) to produce the same descriptive understanding for the patterns of celestial motion as well designed and supported simulations.

Dual coding theory suggests that combining verbal descriptions with kinesthetic and visual interaction with concepts may impact learning to a greater extent than using a single modality approach (Clark & Paivio, 1991; Plummer, 2009). This may be especially important in areas relating to celestial motion as children need to be carefully scaffolded in their development and use of models to explain observations. Attempting to make connections between unobserved rotations and orbits to patterns of apparent motion that occur on timescales of hours or days creates a cognitive load that is not easily juggled by the learner. Thus the use of physical models and kinesthetic (psychomotor) interaction has been successfully explored in learners understanding apparent celestial motion (Plummer, 2009), phases of the moon (Hobson, Trundle, & Sackes, 2009; Trundle, Atwood, and Christopher, 2007), and seasons (Slater, Slater, & Morrow, 2008).

We also approached our instructional design from a constructivist perspective which recognizes that conceptual change requires students to actively engage in their prior knowledge and compare new ideas and models for their usefulness to explain observations (e.g. Duit & Treagust, 1998; Posner et al., 1982; Strike & Posner, 1992). Thus our instruction considers what alternative conceptions students may have and a) develop ways to bring those ideas to the foreground for comparison with new observations and models and b) design targeted activities and instruction to produce conflict with their naïve views. Finally, Vosniadou and Brewer's (1992, 1994) work on children's ideas in astronomy is highly illustrative of the ways in which children combine scientific concepts with their prior naïve world views to produce synthetic ways of understanding the world. This is not necessarily a negative as these synthetic models may be stepping stones towards more sophisticated ways of understanding through additional instruction (Duschl, et al., 2007).

Methodology

Subjects Characteristics and Setting

Eighteen third-grade students participated in the instruction from three different schools, as part of their gifted programs. Most students had visited the school district's planetarium prior to this instruction but had not received sustained instruction on these topics previously. Instruction took place in a separate classroom for gifted instruction. All three schools are part of the same suburban school district. Each elementary school serves approximately 400 students in grade K-3.

Sixteen of the students completed both the pre and post-interviews; this data will be presented. Thirteen of these students were Caucasian; three were Asian. Nine students were male and seven were female. Average age during instruction was 8 years and 8 months.

Instructional design

The instruction used in this study was designed and taught by the co-authors of this paper, as part of the students' gifted programs. Three schools were involved: three students at School 1, six students at School 2, and nine students at School 3 (these students are regularly taught by the second author of this study; the students in the other two schools have a different gifted teacher). Approximately 1 month before instruction, students were asked to complete a series of observation and report their observations on a worksheet. These questions are included in Table 1.

Table 1. Student observing log prior to instruction

OBSERVATIONS OF THE SKY	
<p>When you come home from school today, before you go inside, look for where the sun is. You might not see the sun directly, but you can tell by what part of the sky is the brightest. Look for the moon, too!</p> <p>Then in the morning, the next day, when you walk outside to go to school, look for where the sun is. You might not see the sun directly, but you can see where the sun is rising. Look for the moon too!</p> <p>Use the <u>observation journal</u> provided to write down your observations. These observations should be made for 2-3 days. Then you can answer the questions at the bottom of this sheet.</p> <p>Questions: Please circle your answers</p>	
1.	Was the sun in the same place in the morning and the evening? YES NO
2.	Was the sun high or low in the sky in the morning? HIGH LOW
3.	Was the sun high or low in the sky in the evening? HIGH LOW
4.	Was the sun higher in the morning or the evening? MORNING EVENING
5.	Was the sun in the same part of the sky in both the morning and evening, or was it in different places? SAME PLACE DIFFERENT PLACES
6.	Could you see the moon in the morning? YES NO
7.	Could you see the moon in the evening? YES NO
8.	What did it look like? You can draw a picture if you want.

Instruction was approximately 100 minutes across two consecutive days. A more detailed description of instruction is found in the Appendix. Because nearly all of the students understood that the sun appear to rise in the east and set in the west because of the earth's rotation (as found in the pre-test) the first 30 minutes of the class are mostly review and a chance for the students to become comfortable with the instructional design and familiar with watching the computer program Stellarium (<http://www.stellarium.org>). We began with the apparent motion of the sun using both kinesthetic descriptions in the classroom (using physical direction markers, observations of the actual sun out the window, and the students physically mimicking the path of the sun with their arms) and observations of the sun's motion over time using the computer-based planetarium program Stellarium. Students were asked to kinesthetic model the earth's rotation (by spinning on their own axis) as well as work

with earth globes was used to explain the sun's apparent motion. The instructor and the students then discussed the students' prior observations of the moon and observed the moon's apparent motion on the computer using Stellarium. The lesson ended with students drawing a picture demonstrating their idea of why the moon appears to rise and set.

Lesson two began with a review using Stellarium followed by students "sharing out" their drawings. The students' ideas were discussed and physical models were used to test possible reasons, including the scientific model. The students use the models to understand the slow orbit of the moon relative the rotation of the earth. We discussed the size and distance to the stars with the students and kinesthetically modeling why the stars appear to rise and set. Finally, students drew a new picture representing their idea about why the moon and stars appear to rise and set.

Data Collection and Analysis

Pre interviews were held approximately one month before instruction (because of winter vacation) while post instruction interviews were completed approximately one week after the completion of instruction. The interview began with semi-structured interview questions covering concepts of apparent celestial motion and took place in a small dome with the child using a flashlight to represent the sun, moon or a star (based on interview used in Plummer (2009, in press)). This portion of the interview was audio taped and the students' demonstrations were drawn by the interviewer (first author). The second half of the interview had the children explaining what they demonstrated in the dome using physical models of the sun, earth and moon (based on interview protocol used in Plummer, Zahm, & Rice (2009)). This portion of the interview was recorded on video. A list of interview questions is included in Appendix A.

Primary categories: Each aspect of celestial motion was broken down into multiple categories describing aspects of the students' descriptions (e.g. the sun's path, the sun's rising and setting directions, etc.). A coding scheme for these categories was developed based on previously reported descriptions of children's ideas about apparent and actual celestial motion (Plummer, 2009, in press; Plummer, Zahm, & Rice, 2009) and was modified when necessary to accommodate new ideas uncovered within this sample. This initial coding scheme is included in Appendix B. Both authors independently coded five pre and five post interviews to establish external validity of the coding system resulting in an inter-rater agreement of 92.7%. For all discrepancies, we reviewed the interviews, reached a consensus, and clarified the coding document when necessary.

Learning progression design

Part I – coding of students' explanation of each celestial category's apparent motion:

Secondary codes were created to classify three new secondary categories:

- Sun model: How does the student describe the sun's pattern of apparent motion and then explain that motion?
- Moon model: How does the student describe the moon's pattern of apparent motion and then explain that motion?

- Stars model: How does the student describe the stars' pattern of apparent motion and then explain that motion?

The secondary codes were defined by the primary codes describing individual aspects of the students' understanding. For example, one new code (representing a non-normative conception for the explanation) is "Student gives a generally accurate description of the sun's apparent motion and explains this with the earth's revolution around the sun." The secondary codes were developed based on the nature of the students' responses in this sample; thus future studies could identify additional codes covering new combinations of primary codes.

Examination of the 16 students' pre and post interviews resulted in eight codes for the sun's motion, nine codes for the moon's motion, and ten codes for the stars (Appendix C). These codes were then organized into a scale from most scientifically accurate to least scientifically accurate for each celestial object category (sun, moon or stars). The intermediate stages of the scale were organized according to the accuracy of the explanations and then, within the explanation levels, ranked according to the description of the apparent motion.

Part II – Development of learning progression considering the overall understanding of celestial motion

In the next stage of development, we created the learning progression by combining analysis of the discipline with an assessment of each student's overall understanding of the celestial motion. The goal of this progression is to have a learning progression that ties together all aspects of celestial motion (elementary level). First, a rough outline of the levels was developed by looking at the potential scientific descriptions to anchor the progression (scientific world view) and descriptions based on personal observations (naïve world view) to anchor the initial end of the progression. Previous work on the apparent celestial motion progression (Plummer & Krajcik, 2008) and an understanding of the topics covered in the interviews helped guide this initial outline.

The intermediate levels are more complex as these represent a variety of synthetic world views – students combining both naïve and scientific aspects in their celestial motion descriptions. An iterative approach was used to develop these levels based on examining the secondary codes and looking for trends among the 16 participants. An early trend recognized was the strong tendency among students to have an accurate (or partially accurate) description and explanation of sun concepts but not moon and stars but not the other way around. This helped establish the level between naïve to scientific (least to most sophisticate). We also looked for ways that earlier levels contained ideas that could be built upon and made more sophisticated when moving to the higher level. For example, students who used both the earth's rotation and other inaccurate explanations (such as the sun going around the earth) to explain the sun's apparent motion were placed at a lower level (more naïve) than students who only used the earth's rotation in their explanation of the sun's apparent motion.

Next, all students were re-examined, both pre and post, and classified on the initial learning progression. Any instances where students could not be unambiguously categorized to a level led to either refining specific levels or creating

new levels on the progression. Our progression does not contain all possible levels. For now, it contains primarily levels that we were able to assess in our analysis and levels that were actually observed in the population examined. Future research may lead us to add or modify to accommodate additional synthetic world views.

Finally, we used the learning progression to both measure the impact of the instruction and to assess whether the progression provides a useful scale to use in looking for improvement. This will be discussed later in the paper.

Results of instruction

Prior to instruction, all but one of the students described the sun's path as a smooth curve across the sky, though most erroneously believed that this path goes through the zenith (see Table 2). At least half of the students knew that the sun and moon move east to west and that the stars appear to move. Most of the students also used the earth's rotation to explain the sun's motion but not the moon or the stars. Less than half of the students understood the remaining concepts of celestial motion assessed in the interview, with the weakest areas being the explanation for the motion of the stars, location of the stars and the actual motion of the moon.

We were also interested in looking at how they explained descriptions of apparent celestial motion. To do this, we created secondary categories, based on the primary codes, which combined apparent celestial motion with the students' explanations. This analysis revealed certain tendencies in this population's understanding of celestial motion. Prior to instruction, most students (63%) had a relatively scientific connection between their apparent and actual motions: the sun appears to cross the sky because the earth is rotating on its axis once a day. One additional student gave an inaccurate description of the sun's path but this was explained clearly by the earth's rotation. The remaining students, while giving a generally accurate description of the sun's path, included other explanations, sometimes combined with the earth's rotation (earth revolving around the sun, sun revolving around the earth, or sun moving up/down).

The students' understanding of the moon's motion was less scientific than the sun category, with a range of ideas being represented in the group. Six students (38%) held the scientific view that the earth's rotation causes the moon to appear to move across the sky; however these six students also did not believe that the moon actually moves (a non-orbital model). Another six students held a naïve view, using the moon's motion to explain the moon's apparent motion. This typically included a semi-accurate or inaccurate description of the moon's path across the sky which was explained by the moon orbiting the earth once in 24 hours. Two students combined the two previous models: the moon's path across the sky was explained using the earth's rotation and the moon's 24 hour orbit. The remaining two students believed that the moon does not appear to move and does not actually move. Thus, overall, half the students believed that the moon orbits the earth in 24 hours and the other half believe that the moon does not actually move.

The students' explanatory models for the stars' motion was impacted by their limited understanding of the stars' apparent motion. Seven students had naïve models where the stars motion was caused by their actual motion (3 students) or the stars'

lack of motion was caused by their actual lack of motion (4 students). Half of the students used the earth's rotation to explain the stars' apparent however only two gave a scientific description of the apparent motion combined with the explanation. The remaining six students had inaccuracies in how we would view the stars' apparent motion and how that related to the earth's rotation. This included one student who said that the stars would not appear to move because the earth is rotating and two who said that the rotation would cause the stars to appear to move at the end of the night. One final student used the earth's orbit to explain his non-scientific description of the stars' apparent motion.

Improvement based on instruction

To measure improvement in each of the primary categories, the Wilcoxon signed-ranks test was used (a non-parametric test for related samples; see Table 2). Significant improvement was found across all major areas of celestial motion measured except for three areas in which a large portion of the students began with the accurate notion: the sun appears to move in a smooth curve across the sky, the sun appears to move east to west and the sun appears to move on a daily basis only because of the earth's rotation. However, even with statistically significant improvement, there were still areas in which many of the students did not achieve the scientific understanding. Several students did not describe the stars' apparent motion as east to west and did not believe that we see different stars throughout the night. The moon's actual motion also remained an area where less than half students gave an accurate description.

Table 2 – Number of students who gave scientific descriptions of aspects of celestial motion

	Pre	Post	Z
<i>Apparent Celestial Motion</i>			
Path of the sun is a smooth curve across the sky	15	16	1.00
Not through the zenith	1 (5)	9 (5)	2.45*
Sun moves east to west	11	15	1.63
Path of the moon is a smooth curve across the sky	12	16	2.00*
Moon moves east to west	8	15	2.33*
The stars appear to move	10	16	2.45*
The stars have a path	6	15	3.00**
The stars rise and set	1 (3)	13	3.47***
The stars move east to west	2	8	2.45*
Different stars throughout the night	3	10	2.65**
<i>Explanations</i>			
The sun appears to move because of the earth's rotation	12	13	1.00
The moon appears to move because of the earth's rotation ^a	5 (2)	9 (4)	2.04*
The moon orbits the earth once every month ^a	0(8)	7(7)	2.74**
The stars appear to move because of the earth's rotation	7	13	2.45*
All of the stars are very far away, outside of the sun-earth-moon system	3	10	2.65**

No star: $p > 0.05$; *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$

^aThe number of students who were partially accurate are given in parentheses.

This primary category analysis gives insights to how the instruction impacted understanding, but to look at the “big picture” we wanted to look and changes in how they connected explanation to apparent motion. The secondary categories were ranked from most naïve to most scientific to form a scale for each celestial class (sun, moon, or stars). After instruction, 13 students (81%) connected the sun’s path across the sky with the earth’s rotation. The remaining students continued to have inaccuracies in their explanatory models: the earth revolving around the sun (2) and the sun revolving around the earth (1).

There was also improvement in the moon’s celestial motion: six students (38%) used the earth’s rotation to explain the moon’s path across the sky while also recognizing (without using this to explain the daily motion) that the moon is very slowly orbiting the earth in 28 days (Table 3). Two more students combined the earth’s rotation and the moon’s 28 day orbit to explain the moon’s rising and setting motion (Table 4). Two students explained the moon’s rising/setting with the earth’s rotation though kept the moon fixed (no orbit). Three students combined the earth’s rotation and the moon’s 24 hour orbit around the earth and three more just explained the apparent daily motion with the moon’s orbit (2 with 24-hour orbits and 1 with a 28-day orbit). In consistencies remain in the student’s lunar models but the instruction did impact their use of the earth’s motion and the moon’s orbit in their explanations.

Table 3: Change in children’s understanding of the moon’s orbit

	Pre	Post
Orbits in a month	0	7
Orbits in about a day	8	6
No orbit	8	2

Table 4: Change in how the children explained the moon’s apparent motion

	Pre	Post
Earth’s rotation	5 ^a	7
Rotation & Moon’s orbit	2	5
Moon’s orbit	6	3
Always opposite the sun	8	3

^a Students believe that the moon is always opposite the sun.

Another way to examine the improvement is to examine the ways in which specific models held by students changed due to instruction. For example, before instruction six students said that moon appears to move because it orbits the earth once every 24 hours. In post-interviews, one of those students moved to the accurate model, one moved to using the earth’s rotation plus a 28 day orbit, three students added rotation to their model (so they explained using the earth’s rotation plus the moon’s 24 hour orbit) and one student showed no change. There were also six students with the opposite model initially: the moon appears to move because the

earth rotates and the moon never moves (always opposite the sun). Of these students three moved to an accurate model, one switched to explaining using the moon orbiting in 28 days, and two stayed the same. With such small numbers in our study it is hard to generalize but in most cases the improvements either represented a positive change towards scientific understanding even when the full scientific model was not reached. No specific trends can be seen yet with this small sample size.

There was a clear shift in the students' explanatory models of the stars towards using the earth's rotation to explain the stars' apparent motion (82%). Six of these students gave descriptions of the stars' motion that clearly connected observable features (rising and setting and the concept that we see different stars throughout the night) to their explanation. The remainder (10 students) had non-scientific aspects of their descriptions that suggest they cannot fully apply the earth's rotation to the problem. One additional student gave a scientific description of the stars' apparent motion but explained this with both the earth's rotation and revolution around the sun (for a single day's apparent motion). The remaining two students explained the stars' apparent motion by saying that it is caused by their actual motion around the earth.

Another shift was in the students' understanding of the scale of the sun-earth-moon system compared to the stars' distances. Prior to instruction three students understood that the stars are farther than the sun and moon while after instruction 10 students described this relative scale. However, before instruction, this did not correlate with more accurate explanatory and descriptive models. After instruction five of the six students who gave accurately described the stars' apparent motion and explained this with the earth's rotation also gave a correct description of the scale (with the stars being farther than the sun and the moon). Focusing on both the explanation and the scale may help students make the connections needed to improve their descriptions and their explanations.

Table 5 gives an example of the pre to post levels for one student. While only reaching the highest level of accuracy for the sun category, there is improvement for both the moon and the stars. While more improvement is found in the student's descriptions of the moon and stars' apparent motion, there is change towards a more scientific perspective on the explanations for these motions. This student typifies the trend seen across the students in the study. Using the scale we created as a measurement of movement from naïve to scientific understanding:

- 12 out of 16 students improved for two or more conceptual areas while remaining at the same level of accuracy (often the highest level if the sun) for the third conceptual area.
- 3 students only improved in one area; stayed at same level for the other areas.
- Only one student regressed; he moved to a lower level on our scale for the moon, remained at the highest level for the sun, and improved in description of the stars' apparent motion.

However, this method did not allow us to synthesize and analyze individual's overall model for celestial motion. In the next section we create a learning progression which can be used to classify overall celestial motion models.

Table 5: Example of changes in understanding of celestial motion

ID#	Pre/Post	SUN	MOON	STARS
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113	Pre	Sun-B1: Student gives generally accurate description of sun's motion but explains with earth's rotation and earth revolving around the sun.	Moon-E1: Student does not think moon appears to move or actually moves.	Stars-E3: Stars don't move or move slightly, slowly; explanation is that the stars don't actually move or only move slowly.
113	Post	Sun-A1: Student gives a generally accurate description of sun's motion and explains with the earth's rotation.	Moon-D2: Generally accurate description moon's apparent motion but use moon's 24-hour orbit to explain.	Stars-B1: Accurately describes stars' apparent motion and uses earth's rotation and orbit around the sun to explain this.

Learning Progression for Celestial Motion

The learning progression created for celestial motion was built on the secondary categories described above. The progression is designed to show how students may move from a naïve view towards a scientific view of how actual motions of celestial objects and our position on the earth influences the patterns of motion we can see. However, there are many ways students could describe the combination of the earth/sun/moon/stars motions or lack of motion from an earth-based perspective and solar-system view. So in the development of this progression, we chose to highlight characteristic features of children's models that would help teachers and curriculum developers plan to work with these ideas and to see how intermediate levels can still represent a positive step towards scientific understanding. At this time, the progression is less detailed than a previously developed progression that focused only on the apparent motion (Plummer & Krajcik, 2008).

Table 6 elaborates our learning progression for celestial motion. Appendix C lists the specific secondary codes that were used to assign students to each level of the progression. Three levels are included in which no students populate. The lowest level represents a level of understanding seen in previous research but not this population (Plummer, in press). The last two most scientific contain details not assessed in these interviews (because they were not a focus of this work or the intervention).

Table 6: Learning Progression for Celestial Motion (N=16)

	Pre	Post
Level 1 – Naïve world view	2	1
Level 1-A The child cannot describe the sun as rising and setting. The moon may or may not move but this motion is not a smooth rising and setting. The stars do not rise and set and, other than shooting stars or small motions, do not move.	0	0
Level 1-B The child believes that the sun and moon appear to rise and set (or go up/down) because of their own motion (these descriptions may not be similar to the scientific description). Stars do not move, move a little bit, or move due to their own motion. The earth does not move.	2	0
Level 1-C Children understand that the sun and moon <u>rise and set on opposite sides of the sky and in the same direction</u> . But they use the object's own motion	0	1

(revolution around the earth) to explain. Stars do not move, move a little bit, or move due to their own motion. The earth does not move.		
Level 2 – Synthetic world view	13	7
Level 2-A Student gives a generally accurate description of the earth’s rotation but this is not connected to a generally accurate description of the sun’s apparent motion. Student may also include other inaccurate explanations (such as the sun actually moving). Descriptions of the moon and stars’ apparent motion, and explanations, also contain inaccuracies.	1	0
Level 2-B Student uses the earth’s rotation as well as other inaccurate explanations (such as revolution) to explain a generally accurate description of the sun’s apparent motion (this is the defining characteristic). Descriptions of the moon and stars’ apparent motion, and explanations, also contain inaccuracies.	2	2
Level 2-C Student uses the earth’s rotation as well as other inaccurate explanations for the generally accurate description of the sun’s apparent motion. Either the moon or the stars have a generally accurate explanation for the generally accurate description of the object(s) apparent motion	2	0
Level 2-D Student uses the earth’s rotation to explain a generally accurate description of the sun’s apparent motion but not the moon and stars.	5	2
Level 2-E Student uses earth’s rotation to explain a generally accurate description of the sun’s apparent motion and either the moon or stars, but not both. At this level, students are beginning to make the connection between the earth’s rotation and observed patterns of motion but have not applied this to all possible objects (sun, moon, and stars).	3	3
Level 3 – Scientific world view	1	8
Level 3-A The child describes the sun, moon and stars as rising and setting in the same direction across the sky (there may be a lack of sophistication in the path details but they generally follow the scientific trend for daily motion). The child uses the earth’s rotation to explain these motions. But there are still inaccuracies in description of the moon’s actual motion or how that motion is involved in the moon’s apparent motion.	1	3
Level 3-B The student describes the sun, moon and stars as rising and setting in the same direction across the sky (there may be a lack of sophistication in the path details but they generally follow the scientific trend for daily motion). The child uses the earth’s rotation to explain these motions. The child understands that the moon orbits the earth once a month but that this is not the cause of the moon’s daily rising and setting.	0	5
Level 3-C [Not assessed in the study] The student understands that the earth orbits the sun once a year but that this is not the cause of the sun’s rising and setting or the daily motion of the stars. Student is able to apply the earth’s orbit to explaining why we see different stars at different times of the year.	n/a	n/a
Level 3-D [Not assessed in the study] In addition to the above descriptions, the student understands that the sun does not pass through the zenith from their location [ultimately will explain this with the shape of the earth and the tilt of the earth].	n/a	n/a

With few students in our study, there is a limitation to which we can test this progression. However, we can use this progression to show that 12 of the 16 students (75%) moved towards the scientific levels on the progression. Three students did not

change their level and one regressed down a level. One of the strengths of using the learning progression methodology with this conceptual area is that we can see that half (50%) of the students are now using the earth's rotation to explain the daily motion of the sun, moon and the stars (the three students who ended at Level 3A did not completely understand the moon's orbit).

Not surprisingly, examining individual student improvement along the progression suggests that the students who started at the lowest, most naïve, levels of understanding are less likely to progress to the scientific level of understanding than those who started at the higher synthetic levels. Of the five students at Level 1 and Levels 2A and 2B, only 1 progressed beyond level 2D (that student reached full accuracy – 3B). Of the 11 who started at 2C or higher, 7 progressed to scientific (64%).

Discussion and Implications

Building the learning progression

This learning progression builds on our previous work with children's understanding of apparent celestial motion (Plummer & Krajcik, 2008), taking the next logical step to build a progression around a robust explanatory model. The learning progression we developed shows promise for use in assessing where individual student's understanding of celestial motion lies and how particular instruction helps student move towards a more coherent scientific understanding. The levels were first developed based on the students' understanding of the concepts and were then arranged as a scale based on analysis of the discipline. The trend of students to move upwards on this scale confirms its usefulness as an indicator of progress and as a tool for analyzing curriculum and instruction (in this case, revealing problematic areas of the instruction such as the use of the moon's orbit and the concept that different stars are seen throughout the night). It also illustrates the importance of probing students' descriptions and explanations across the sun, moon and stars to uncover where instruction has been unsuccessful at moving students towards more coherent scientific models of motion in the solar system. The learning progression we present here is an initial attempt to suggest ways of looking at this concept area. We have not yet explored all of the subtle complexities in these motions or looked in depth at how this could help us build towards other more sophisticated understandings such as the seasons or phases of the moon.

Our development of a learning progression around the big idea of celestial motion allows us to examine children's whole model of celestial motion place it on a scale of understanding. In this study, most (81%) of the sixteen children began at what we termed an intermediate or synthetic model of the celestial motion system. This represents a range of ideas combining scientific and non-scientific descriptions and explanations organized according to first, the accuracy of the sun-earth system, and then the application of the earth's rotation to the apparent motion of the moon and stars. Vosniadou and Brewer (1994) also looked at ways to classify, organize and rank students' mental models for the day-night concept and the motion of the sun, moon and stars. Our study goes beyond Vosniadou and Brewer's previous work by explicitly asking students to discuss their earth-based observational perspective and then asking them to shift to a new perspective and offer an explanation. Their study

did not explicitly examine the distinction between actual and apparent motions leaving questions about the students' abilities to explain and interpret.

One of the goals of the movement towards developing learning progressions is to create descriptions that can be used by assessment writers, policy makers, curriculum developers, and in teacher training. We believe that our work can help begin to provide insights into these areas. Developing assessments around these complex, moving, three-dimensional, frame-changing concepts will be challenging. But creating assessment items that address specific features that are characteristic each level of the learning could help evaluate learners. This work should also be beneficial to curriculum developers and teachers by helping them recognize the variety of ways in which children enter the classroom through their understanding and identifying the positive aspects of those naïve and synthetic models to move them towards scientific understanding. This should allow curriculum developers in the future to design educative curriculum (Davis & Krajcik, 2005) to help them examine their own understanding with respect to this progression as well as providing tools to improve their teaching practice in ways that will improve their content knowledge. Many elementary teachers also hold synthetic rather than fully scientific models of celestial motion (Plummer, Zahm, & Rice, 2009).

Use of instruction in learning progression development

Part of developing this learning progression was to develop an instructional intervention designed to improve the students' ability to move between apparent and actual motion frames of reference and then compare outcomes to movement along our progression. Each third grade student who participated in this study showed improvement in some aspect of their ability to describe and/or explain celestial motion. However, no student in the study reached the full scientific understanding of the concepts included in the instruction. This is not surprising due to the complexities of the motions and the short time frame of the instruction. Students who did not use the earth's motion to explain the sun's motion initially improved but did not reach higher levels of overall understanding (for sun, moon and stars). This suggests that students without a strong foundation (the earth's rotation relating to the sun's apparent motion) will need more time spent on sun-earth concept before improving all areas of celestial motion. While most students were able to accurately describe the apparent motion of the moon on a daily basis, the concept that this is due to the relatively rapid rotation of the earth compared to the relatively slow orbit of the moon proved to be a challenge for many students. Students also found the idea that the stars appear to rise and set in a similar fashion to the sun and moon a challenging concept and some students gave inaccurate descriptions of the stars' apparent motion while at the same time accurately explaining this motion with the earth's rotation. Future instruction will need to address the relationship between students' understanding of the distance and size of the stars to their explanation for the stars' apparent motion. We engaged the students in discussion about stars that were far larger and more distant than the sun but failed to convince some students that this also meant there were no smaller closer stars within the solar system.

Our instructional design considered several theoretical perspectives relating to how students learn particular to this domain:

- Students lack an understanding of the earth-based perspective from which to develop explanations. To fully understand, children need to have an evidence based perspective to explain (Plummer, in press, 2009; NRC, 1996).
- Combining verbal descriptions with kinesthetic and visual interaction with concepts can impact learning to a greater extent than verbal or written alone (Paivio, 1986; Plummer, 2009).
- Conceptual change requires students to actively engage in their prior knowledge and compare new ideas and models for their usefulness to explain observations.
- Learners move from naïve views of the world towards scientific views through synthetic ways of understanding the world (Duschl et al., 2007; Vosniadou & Brewer, 1992, 1994).

We then used these perspectives to interpret the interaction between our instruction, assessment, and student learning.

Students who participated in this instruction improved, in general, in the ways which we predicted according our theoretical perspective. We attribute improvement in the students' overall models of celestial motion to the iterative nature of the instruction. Students were provided with the opportunity to make predictions and then observe simulations of the apparent motion of celestial objects. Students need a clear context in which to connect new knowledge and integrate with existing ideas. Our perspective focuses on providing students with an earth-based understanding to motivate an explanation. Thus by seeing great gains in students' observational perspective of apparent celestial motion is promising towards this approach.

Students then offered their own personal explanations for these observations followed by guided modeling (where students engaged in this modeling practice in a kinesthetic fashion using their own bodies and views to recreate the scientific explanations). Thus students had the opportunity to compare their own ideas to scientific explanations in order to modify their existing models through a multi-modality approach (Paivio, 1986; Clark & Paivio, 1991; Druyan, 1997; Plummer, 2009). The outcomes measured from this instruction confirm that children were modifying their existing explanations to incorporate the scientific perspective in ways that were consistent with their improved knowledge of apparent celestial motion. And often we saw changes that reflect growth but not full adoption of the scientific model; students created new synthetic models that kept aspects of their initial ideas but included more scientifically sophisticated ideas (Vosniadou & Brewer, 1992, 1994). These changes should be valued; we also observed that students who held useful synthetic model were able to modify those models and achieve the scientific level on our learning progression.

Our development of a learning progression allowed us to describe how students' overall understanding became more or less empirically accurate, logically consistent, and sensitive to issues of simplicity after participating in this instruction (Vosniadou & Brewer, 1994). Vosniadou and Brewer argued that as children learned scientific conceptions in school their mental models become more inconsistent. This stage of synthetic notions and inconsistencies may be represented in the initial conceptions these students had, coming into instruction. Their models of celestial motion were a mixture of scientific ideas and naïve notions based on observations of the world. However, the analysis of the post-instruction conceptions articulated by the students revealed a tendency towards greater empirical accuracy and logical consistency as

many of the students moved towards the use of the abstract scientific model in their answers. These movements from naïve descriptions in which the observed and actual motion of the sun, moon and stars are equivalent, through a mixture of inconsistent descriptions and explanations, towards a more consistent and scientific explanation is the basis of the learning progression for celestial motion we have developed.

Limitations and direction for future research

A few factors limit our ability to generalize our findings beyond this project. First, our population of focus was a small group of “gifted” students. Thus their initial knowledge level, and possibly their capacity to apply the instruction to solving problems, may not be representative of the “average” third grade students. However, as an exploratory pilot study we can use the results to make recommendations for future instruction and future research. The learning progression we developed will be useful as a preliminary tool to compare and adapt based on future interviews with children around these concepts. Our analysis of the students’ response to the instructional intervention uncovers areas that continue to be problems for this gifted population which should be considered and addressed on future instruction with other population. Further, the improvement seen using our combination of improving apparent motion understanding through simulations and explanations through modeling is suggestive as a promising approach for all elementary populations.

Future research is needed to fully understand how children come to adopt the scientific model for celestial motion. Research with general classrooms in elementary grades will help us develop a more robust representation of the progression from naïve to scientific. This work will require additional research on instructional design as movement towards scientific will not occur in a vacuum. We are interested in examining the classroom-planetarium connection in order to understand how knowledge of apparent celestial motion acquired in the planetarium can be harnessed in the classroom and explained using kinesthetic modeling activities. We are interested in examining how planetarium instruction may provide different learning opportunities compared to 2D computer screen simulations. Future research should examine ways to extend this learning progression to understand how development of these celestial motion concepts contributes to a full understanding of seasonal changes in the star patterns, lunar phases, and the seasons. This would suggest that future learning progression work will move divergently from this big idea of celestial motion rather than pulling strands together to understand one single larger explanatory model.

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Appendix A: Interview Questions

Versions of this protocol has been used in previous studies (Plummer, in press, 2009; Plummer, Zahm, & Rice, 2009).

Apparent celestial motion

The students will use a flashlight to demonstrate their answers in a mini-dome:

1. Sun's apparent motion today
 - a. Can you show me where the sun is first thing in the morning?
 - b. Can you show me the sun's apparent motion throughout the day?
 - c. What happens at the end of the day?
 - d. Where is the sun at noon?
 - e. Would that be directly over your head?
2. Motion of the moon
 - a. Does the moon appear to move across the sky?
 - b. (If the moon appears to move) Can you show me what that looks like?
 - c. (If the moon appears to rise and set) When does the moon rise? When does the moon set?
 - d. Are there times when we cannot see the moon? Why can't we see it? Can you think of any other reasons?
3. Motion of the stars
 - a. You showed me the motion of the sun and the moon. Do the stars appear to move at night too?
 - b. (If yes) Pretend the flashlight is showing one bright star. Can you show me the motion of that star?
 - c. Do we see the same stars all night long? Why or why not?
 - d. What happens to the stars when the sun comes up in the morning?

Actual celestial motion

Ask the subjects to use a model of the sun (a ball), the earth (a small globe), and moon (a small ball) to describe why they showed the sun, moon and stars' apparent motion. Have the student put a sticker on the earth to show his/her location.

1. Can you use these objects to explain why the sun appears to move across the sky as you showed in the dome? (Prompt the student to indicate when sunrise, noon and sunset are occurring.)
2. Can you use these objects to explain why the moon appears to move (or not move) like you showed in the dome?
 - a. Can you use these objects to explain why we can't see the moon some of the time?
3. Where would the stars be in this model? When would we be able to see them?
4. Can you use these objects to explain why stars (do not) appear to move?

Appendix B: Primary Categories - coding document

1. **Sun-Opp**: Does the sun rise and set on opposite sides of the sky?

Accurate: A smooth path that rises and set more than 45 degrees apart.

Non-normative: Any other type of path, including paths with sharp turns, or that goes straight up and down.

2. **Sun-EW:** Does the sun rise in the east and set in the west?

Accurate: Sun rises in the eastern hemisphere of the sky and sets in the western hemisphere (e.g. rising SE and setting SW is accurate).

Non-normative: Any other combination of rising and setting positions.

3. **Sun-Zen1:** Does the sun pass below the zenith? Base answers on the initial questions about the sun's path. (Based on responses for the sun's path on THIS DAY.)

Accurate: Sun does not pass through the circle at the top of the dome AND the student says that the sun does not pass directly overhead.

Partially accurate: Inconsistent – Indicates both that the sun is below the zenith but also that it goes through the zenith through a mis-match in their verbal response (e.g. no it is never overhead) and demonstration (e.g. passing through the zenith)

Non-normative: Sun passes through the zenith (both in demonstration and verbal answer).

4. **Sun-Zen2:** Does the sun ever pass through the zenith? (Now students are asked if the sun EVER passes overhead, not just on the day that they are being questioned about.)

Accurate: No, both in demonstration and verbal responses.

Partially accurate: Inconsistent between verbal response and visual demonstration.

Non-normative: Yes in any of the demonstrations or verbal responses.

5. **Moon-move:** Does the moon appear to move?

Accurate: A verbal response of “yes” or description of a path

Non-normative: A verbal response of “no” or “I don't know”

6. **Moon-Opp:** Does the moon rise and set on opposite sides of the sky?

Accurate: A smooth path that rises and set more than 45 degrees apart.

Non-normative: Any other type of path, including paths with sharp turns, or that goes straight up and down.

7. **Moon-EW:** Does the moon rise in the east and set in the west?

Accurate: Moon rises in the eastern hemisphere of the sky and sets in the western hemisphere (e.g. rising SE and setting SW is accurate).

Non-normative: Any other combination of rising and setting positions.

8. **Moon-Sun:** Does the moon follow the same type of path as the sun?

Accurate: Same direction, same overall appearance and angle of path as the sun.

Non-normative: Paths are different in form.

9. **Stars-Move:** Do the stars appear to move?

Accurate: A verbal response of “yes” or description of a path

Non-normative: A verbal response of “no” or “I don't know”

10. **Stars-Path:** Do the stars appear to follow a smooth path in a continuous motion?

Accurate: Motion is smooth, in one direction, and continuous. This could include rising and setting, a smooth arc around the sky, or a circular motion.

Non-normative: Could include moving in multiple directions, many stars in many directions, or no movement. Also includes saying the stars appear to move but not demonstrating that motion. Also includes answers of “I don't know.”

11. **Stars-Opp:** Do the stars appear to rise and set on opposite sides of the sky?

Accurate: Demonstrates that a star rises and sets on opposite sides of the sky and says that the stars rise and set (if asked).

Partially accurate: Either does not demonstrate rising and setting but answers “yes” when asked if they rise and set, or demonstrates that a star rises and sets but answers “no” when asked if stars rise and set.

Non-normative: Stars do not appear to rise and set.

12. **Stars-EW:** Do the stars appear to rise in the east and set in the west?

Accurate: Demonstrates that a star appear to rise in the eastern side of the sky and set in the western side of the sky.

Non-normative: Any other demonstrations or stars do not appear to move

13. **Stars-Diff:** Do we see different stars throughout the night?

Accurate: Requires an accurate answer (with an accurate explanation)

Non-normative: Either we do not see different stars or the explanation is incorrect

14. **Stars-Day:** Are the stars still in the sky during the daytime?

Accurate: Student believes that the stars are still in the sky during the day.
(Explanation does not have to be accurate but put this in the justification.)

Non-normative: Student indicates that the stars are not in the sky during the day.

29. **Rotation:** Does the student accurate describe and/or demonstrate the concept of the rotation of the earth?

Accurate: Student clearly demonstrates that the earth rotates on its axis (or gives an accurate verbal description that cannot be confused with other concepts)

Non-normative: Does not include a demonstrate or clear explanation of rotation

30. **ExSun:** Does the student use the rotation of the earth to explain why the sun appears to move across the sky?

Accurate: Student models the earth rotating (in one direction) when asked why the sun appears to move. Does not include other motions to explain the sun's motion.

Non-normative: Student uses other kinds of motion (and may also include rotation) to explain why the sun appears to move.

31. **ExMoon:** Does the student use the rotation of the earth to explain why the moon appears to move across the sky?

Accurate: Student models the earth rotating (in one direction) when asked why the moon appears to move. Does not include other motions to explain the moon's motion.

Non-normative: Student uses other kinds of motion (and may also include earth's rotation) to explain why the moon appears to move. Or says that the moon does not appear to move.

32. **Orbit:** Does the moon orbit the earth about once a month?

Accurate: The moon orbits the moon once a month

Partially Accurate: The moon orbits the moon but in less than 27 days or more than a month

Non-normative: Any other response

33. **Moon-visible:** Does the student recognize that sometimes the moon is not visible because it is on the other side of the earth?

Accurate: Says or demonstrates that the moon is on the other side of the earth

Non-normative: Any other response – list in Justification

34. **ExStars:** Does the student use the rotation of the earth to explain why the stars appear to move across the sky?

Accurate: Student models the earth rotating (in one direction) when asked why the stars appears to move. Does not include other motions to explain the stars' motion.

Non-normative: Student uses other kinds of motion (and may also include earth's rotation) to explain why the stars appears to move. Or says that the stars do not appear to move.

35. **Where are the stars?**

	A. Farther away than the sun and moon
	B. Sun are closer and some are farther than the sun and moon

	C. Farther than the moon but closer than the sun
	D. Closer than both the sun and moon
	E. Same distance as sun and moon.
	F. Around the moon
	Unknown/unclear

Appendix C: Secondary Categories

Categories for Student Connections between Apparent Motion and Actual Motion

None of these categories consider the accurate use of direction. In other words, a “generally accurate” refers to a smooth path across the sky but does not need to go from E to W.

The Sun

Sun-A1	Sun-A1: Student gives a generally accurate description of sun’s motion and explains with the earth’s rotation.
Sun-A2	Sun-A2: Student gives inaccurate description of the sun’s rising and setting and uses the earth’s rotation to explain this.
Sun-B1	Sun-B1: Student gives generally accurate description of sun’s motion but explains with earth’s rotation and the earth revolving around the sun.
Sun-B2	Sun-B2: Student gives generally accurate description of sun’s motion but explains with inaccurate description of earth’s rotation and the earth revolving around the sun.
Sun-B3	Sun-B3: Student gives a generally accurate description of the sun’s motion and explains with the earth’s revolution around the sun.
Sun-C1	Sun-C1: Student gives generally accurate description of sun’s motion but explains with earth’s rotation and the sun revolves around the earth.
Sun-C2	Sun-C2: Student gives generally accurate description of sun’s motion but explains using the sun going around the earth.
Sun-D1	Sun-D1: Sun moves up/down because sun is actually moving up/down.

The Moon

Moon-A1	Moon-A1: Generally accurate description of the moon’s apparent motion and uses the earth’s rotation to explain. Moon orbits once a month.
Moon-A2	Moon-A2: Generally accurate description moon’s apparent motion but uses earth’s rotation and moon’s 28 day orbit to explain daily motion.
Moon-B1	Moon-B1: Generally accurate description of the moon’s apparent motion and uses the earth’s rotation but the moon does not orbit and/or stays on opposite side from the sun.
Moon-C1	Moon-C1: Generally accurate description moon’s apparent motion but uses earth’s rotation and moon’s 24 hour orbit to explain.
Moon-C2	Moon-C2: Generally accurate description moon’s apparent motion but uses earth’s rotation and moon’s 24 hour orbit to explain. And Moon is always opposite Sun.
Moon-D1	Moon-D1: Generally accurate description moon’s apparent motion but uses moon’s 28 day orbit to explain daily motion.
Moon-D2	Moon-D2: Generally accurate description moon’s apparent motion but use moon’s 24 hour orbit to explain.
Moon-D3	Moon-D3: Student gives inaccurate description of moon’s motion and

	uses moon's 24 hour orbit to explain.
Moon-E1	Moon-E1: Student does not think moon appears to move or actually moves.

The Stars

Stars-A1	Stars-A1: Accurately describes stars' apparent motion and uses earth's rotation to explain this.
Stars-A2	Stars-A2: Accurately describes stars' apparent motion (except for seeing different stars during the night) and uses earth's rotation to explain this.
Stars-A3	Stars-A3: Stars appear to move, but student gives inaccurate description of stars' motion and uses earth's rotation to explain this.
Stars-B1	Stars-B1: Accurately describes stars' apparent motion and uses earth's rotation and orbit around the sun to explain this.
Stars-C1	Stars-C1: Stars do not move; student uses earth's rotation to explain that stars only set at end of the night.
Stars-C2	Stars-C2: Stars do not move but student explains this with the earth's rotation
Stars-D2	Stars-D2: Gives inaccurate description of stars' motion; explains by using the earth's orbit around the sun.
Stars-E1	Stars-E1: Accurately describes stars' apparent motion but uses stars' actual motion to explain this.
Stars-E2	Stars-E2: Gives inaccurate description of stars' motion; explains by using stars moving around the solar system.
Stars-E3	Stars-E3: Stars don't move or move slightly, slowly; explanation is that the stars don't actually move or only move slowly.