Challenges in defining and validating an astronomy learning progression

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Introduction

This chapter focuses on challenges in developing and validating a learning progression in the domain of astronomy. These challenges are not unique to this domain; considering them may be illustrative for researchers working in other areas. As an astronomy education researcher, I view learning progression-based research as having the potential to provide needed coherence and direction for the field. In general, astronomy education receives a small allotment of instructional time (Plummer & Zahm, 2010). Yet current instruction in astronomy, like other areas of science, is likely to be characterized as fragmented, focused on breadth rather than depth, and emphasizing inconsequential facts rather than the core of the disciplines (Kesidou & Roseman, 2002). This suggests that teachers, through their use of fragmented curriculum, may not be taking full advantage of the short amount of time allocated to astronomy content. In addition, the current research base lacks a defined coherence across conceptual topics and has a limited coverage of instructional interventions (see Bailey and Slater, 2003 and Lelliott and Rollnick, 2010 for reviews) – work that is needed to move the field forward in ways that can help teachers, as well as curriculum and assessment developers.

Through analysis of the logical structure of astronomy, review of relevant astronomy education literature, and consideration of learning progression research, I examine two areas necessary for defining a learning progression in astronomy: identifying the focus of the learning progression and obtaining empirical support for defining the learning progression which includes validating the levels of increased sophistication in the content. Within these two areas, I discuss the following challenges that arose in defining a learning progression in the domain of astronomy.

1. *Identifying the learning progression focus:* The first challenge explored is determining what constitutes a "big idea" in the domain. As explained below, I chose the big idea of celestial motion. This choice leads to the second challenge: developing sophistication in celestial motion is specifically tied to learning about a finite set of observable phenomena. These phenomena define the conceptual space for learning celestial motion and place a limit on the available contexts in which to learn about this big idea. This lead to a third challenge: defining the learning progression in a way that values the importance of both understanding observations from an earth-based perspective and learning the explanations for these observations. The fourth challenge considers how we make adequate links to other big ideas and therefore other learning progressions.
2. *Obtaining theoretical and empirical support:* While some areas of astronomy are well-explored in the research literature, the fifth challenge explored in this chapter is that there are many areas that have not been extensively researched, thus limiting our ability to describe how children learn across time. The sixth challenge examines how to obtain further empirical

evidence to begin the process of validating the hypothetical learning progression given limited student knowledge of even the most basic concepts and limited inclusion of astronomy in the curriculum.

In this chapter, I explain these challenges and propose potential solutions that may help the field move forward, in this domain and others.

Identifying the Learning Progression Focus

Identifying the focus for a learning progression includes articulating the big idea, a unifying concept that help make sense of a broad variety of phenomena, situations, and problems; big ideas provide great explanatory power for the world around us (Smith, Wiser, Anderson, & Krajcik, 2006). The learning progression describes how a learner may develop understanding of a big idea in increased sophistication across time and through appropriate instruction (Smith et al., 2006). At one end of a learning progression is the upper anchor: the level of scientific understanding of the big idea as determined by societal goals for students. At the lower anchor of the learning progression is a description of what children know and their reasoning ability as they enter school (National Research Council [NRC], 2007). In this section, I will articulate the challenges that arose in making the choice of celestial motion as a big idea in astronomy.

Challenge #1: Identifying Big Ideas in Astronomy

Choosing an appropriate big idea for the domain of astronomy is the first challenge discussed in this chapter as the answer is not obvious or clearly agreed upon by astronomy education researchers. Big ideas are descriptions of powerful explanatory models that have far reaching ability to explain a broad range of observable phenomena (National Research Council [NRC], 2007). Many possible big ideas might be chosen for the development of learning progressions. Beyond the general goal stated above, I add additional criteria for choosing big ideas in astronomy:

1. Big ideas are those that are important to the field of astronomy. Astronomy, as a science, is concerned with describing and explaining the universe as a whole. Thus big ideas in astronomy are those that represent ways of knowing and understanding the universe.
2. Big ideas describe explanatory models that can be learned by beginning with a child's observations of the world. This begins to capture the "increasing in sophistication" criterion generally accepted in the definition of learning progressions (Corcoran, Mosher, & Rogat, 2009; NRC, 2007; Wiser et al., 2006).
3. Big ideas can explain multiple, unified astronomical phenomena such that learning to explain an individual phenomenon helps the learner build in sophistication towards the big idea and, thus, explanations of additional phenomena.

My research has focused on developing a learning progression for the big idea 'celestial motion.' The big idea of 'celestial motion' can be described as a response to the question: *how* *do we explain our earth-based perspectives of astronomical phenomena using the actual motions and properties of celestial objects?* Astronomical phenomena observed from an earth-based perspective (such as the patterns of apparent daily motion, seasonal changes, and the phases of the moon) can be explained using the earth's rotation and tilt, the earth's orbit around the sun, and the moon's orbit around the earth (Plummer & Krajcik, 2010, p. 2).

Ultimately, the big idea of celestial motion combines two concepts: *motions of celestial objects* and the observer moving between *frames of reference* to understand observable phenomena. The various phenomena explained by this big idea are not caused by the same underlying motions; however, explanations of these phenomena are unified by reliance upon the motion of celestial objects. In this chapter, several terms are used to describe critical features of the big idea. An *earth-based perspective* is used to describe more than just a single observation of the sky; rather I use this term to describe what a particular celestial object looks like from the earth across time (such as the sun rising and setting or the changing phases of the moon). This contrasts with the *heliocentric model* (also referred to as the *explanatory motion*) that describes what is actually happening in the solar system – the actual rotation or revolution of celestial bodies – and explains our earth-based perspective. These two perspectives are each *frames of reference* from which we may define our description of a phenomenon. In this section, I explain the choice of this big idea as the learning progression upper anchor, describe other possible big ideas in astronomy, and discuss the challenges I have found in choosing a big idea in astronomy.

To select and define this big idea, I did two things. First, I consulted policy documents (American Association for the Advancement of Science [AAAS], 1993; NRC, 1996) and research syntheses (Adams & Slater, 2000; Agan & Sneider, 2003 Bailey & Slater, 2003; Kavanagh, Agan, & Sneider, 2005) and considered the logical conceptual structure of the domain. Second, I chose an explanatory model that provides coherence among the aspects of astronomy that are first accessible (through personal and cultural experience) to young children. Specifically, the following topics are part of the same big idea of applying the motion of celestial objects to explain observations from an earth-based perspective: daily patterns in the apparent motion of the sun, moon and stars; lunar phases; yearly patterns in the motion of the sun and stars; the reason for the seasons; and the motions of other solar system objects, such as the planets. Explaining the earth-based perspectives with the actual motions of other objects can ultimately be drawn upon to understand other phenomena in the universe, such as our observations of pulsars and the shapes of planetary nebula. Understanding these apparent patterns of motion also requires understanding of the earth's shape, as well as size and distance, both within the solar system and beyond (e.g., the relative distance to the stars). These concepts of celestial motion form the foundation for understanding the major concepts of astronomy included in K-8 astronomy curricula (Palen & Proctor, 2006; AAAS, 2001; NRC, 1996).

One of the goals of developing learning progressions is to deepen the focus of science education on central concepts rather than spending time on topical and inconsequential ideas. By focusing on celestial motion as an overarching 'big idea' we are moving the focus away from these individual phenomena (e.g. day/night cycle, phases of the moon, seasons) and putting more emphasis on connecting observations to the underlying explanatory motions across multiple contexts in the hopes of providing a more unified, integrated understanding of motions in the solar system. While not having the status of a universal theory, such as the Big Bang theory or the Universal Theory of Gravitation, celestial motion fits the criteria for big ideas in that it provides organization across a range of concepts in the domain and offers explanatory power with respect to a wide range of phenomena. It also provides a useful framework to organize children's initial explorations in astronomy at a level that is accessible to them. Children have beliefs and personal observations regarding the appearance and apparent motion of the sun, moon and stars (e.g., Plummer, 2009a; Vosniadou & Brewer, 1994). It is focused on a specific way of knowing that is important to understanding in astronomy: making observations of phenomena and then interpreting them in light of potential, unobserved motions. The concepts of rotation and revolution explain phenomena beyond the solar system and thus will form a foundation for discussing some advanced topics in astrophysics (binary stars, extrasolar planets, clusters of galaxies, pulsars, etc.).

However, celestial motion is not the only big idea which could be selected; other researchers have proposed alternative big ideas for astronomy. Lelliott and Rollnick (2010) reviewed Project 2061 science standards (AAAS, 2001), leading to their suggestion of eight big ideas: gravity, the solar system, stars, size and distance, earth shape, the day/night cycle, the seasons, and the earth/sun/moon system. Lelliott and Rollnick suggest these as potential big ideas because they represent concepts that are commonly taught in school and that have been the subject of extensive ongoing educational research. While clearly drawn from standards and the literature base, these concepts do not help us see how students will build in sophistication across the domain. Gravity is certainly a big idea, encompassing broad explanatory power for understanding an extensive array of phenomena; however, the other suggested big ideas are topics rather than explanatory models, do not represent useful ways of understanding the world, and do not provide coherence for the learner.

Slater and Slater (2009) evaluated existing standards and drew upon the expertise of astronomers and astronomy educators to come up with a list of 11 broad categories in astronomy that they link to the overarching big idea of the Big Bang theory. These 11 categories are: moon phases, daily/diurnal patterns, yearly patterns, size and scale, seasons, evolution and structure of planetary systems, stars and stellar evolution, formation of the universe, formation of elements, electromagnetic radiation, and gravity. While the Big Bang theory is undeniably an overarching and extremely important theory in science, a smaller grain-size big idea is needed to inform curriculum and standards that are useful for K-12 schooling. Ultimately, understanding how these concepts all link to the Big Bang theory could be a goal of education in astronomy. Thus, instead of beginning with the Big Bang as a big idea for a learning progression, we might view those categories that are built in sophistication across multiple years (such as electromagnetic radiation, gravity, and perhaps stellar evolution) as potential big ideas that are a better fit to the criteria above. Further, four of Slater and Slater's categories can be subsumed within the celestial motion learning progression (moon phases, diurnal patterns, yearly patterns, and seasons); thus, I suggest that increasing in sophistication in celestial motion is a potential step towards the big idea of the Big Bang theory.

Challenge #2: Balancing the variety of phenomena within the big idea

Within the commonly used definitions of learning progression, *learning performances* represent the ways in which students may express understanding of the big idea at different levels of sophistication (Corcoran et al., 2009; NRC, 2007; Smith, Wiser, Anderson, & Krajcik, 2006). Determining these learning performances may potentially be constrained by the nature of phenomena appropriate for the progression. In Smith et al.'s (2006) K-8 atomic-molecular theory learning progression, learning performances are largely unconstrained by particular phenomena; students may learn about materials and properties of a wide range of objects in nearly any context. Similarly, learning performances associated with the genetics learning progression developed by Duncan, Rogat, and Yarden (2009) have the flexibility to address a wide range of phenomena explained by the function of proteins in living organisms. In contrast, observable phenomena in the celestial motion domain are constrained to a finite set of options. These phenomena include the day/night cycle, daily observable patterns of rising and setting, the phases of the moon, eclipses, seasonal and latitudinal changes associated with changes in the sun's path, and seasonal star patterns. Other potential phenomena include tides and retrograde motions of the planets. Each phenomenon is coupled with a distinct set of explanatory motions rather than a single underlying explanation, as is the case for the genetics and molecular theory learning progressions. For example, learning to express an understanding of the relationship between the earth's rotation and our earth-based observations is limited to the apparent motions of the sun, moon and stars. Learning performances related to the effects of the moon's orbital motion are constrained to our own earth-moon system.

Thus, the second challenge in defining this learning progression arises in the specification of learning performances for celestial motion; doing so requires exploring how each of these specific, but finite, contexts contributes to the overall model of observation and motion in the solar system (see Table 1, discussed below). This is in contrast to using a large number of contexts, or phenomena, to help the learner generalize the big idea as occurs in some other learning progression research. If we focus too much on celestial motion as a generalized concept ('rotation and revolution in the solar system explain observable phenomena'), we lose the focus on how students learn to explain individual phenomena. For example, just understanding the moon's orbit is not enough to understand why the moon's appearance changes. Students' ability to use the underlying conceptual model to generate explanations requires that they initially begin with something more concrete than a generalized knowledge of rotation and revolution. Instead, their knowledge of celestial motion begins from instruction that is highly contextualized in the familiar observable phenomena. We hope that, through appropriate instruction, students will eventually reach a more inter-connected and broad-perspective view of celestial motion.

Increased sophistication, from the lower to upper anchor of the learning progression, may mean that students learn to work on different time scales and combinations of motion to explain more complicated phenomena. In some cases, this may mean learning to explain the same phenomena in more sophistication. For example, students may initially learn that the moon rises and sets once every 24 hour period due to the earth's rotation. Later they could learn that the moon appears to rise and set about 50 minutes later every day because of the moon's monthly orbit. Thus increased sophistication includes additional time scales and the addition of new motions. In other cases, students may apply concepts they learned with respect to one phenomenon (such as explaining sun's rising and setting with the earth's rotation) as part of a more sophisticated explanation (such as including the earth's rotation in an explanation for the seasons).

To provide the coherence that is a core goal of learning progression-based research, while also acknowledging the central importance of the specific phenomena that are associated with the domain, the learning progression proposed here uses the actual motions of celestial objects (explanatory motions) as the back-bone for the progression while explicitly connecting to the observable phenomena. Table 1 shows how these underlying motions (earth's rotation, earth's orbit, etc.) can be combined in increasingly complex ways to explain earth-based observable phenomena.

Table 1

An Exploration of the Role of Heliocentric Motions in a Learning Progression for Celestial Motion

Object-motion	Relevant phenomena
Earth-rotation	Day/night cycle; Daily apparent motion of sun, moon, stars, etc.
Earth-rotation + Moon-orbit	Lunar phases
Earth-rotation + Moon-orbit + Earth-orbit	Eclipses
Earth-rotation + Earth-orbit + Planet-orbit	Apparent motion of planets and retrograde motion
Earth-rotation + Spherical Earth[a]	Difference in visible constellations with latitude and circumpolar constellations
Earth-rotation + Earth-orbit	Seasonal stars
Earth-rotation + Spherical Earth[a] + Earth-tilt + Earth-orbit	Change in sun's path across the earth's surface and the seasons to explain the seasons

[a] While the concept of a spherical earth is not a motion, as is rotation or orbit, it is our own motion in moving across the spherical surface of the earth that causes certain astronomical phenomena such as visibility of constellations and differences in seasonal change.

Table 1 is not a learning progression in the sense that it does not show a direct progression from naïve ideas, through more and more sophisticated ideas, towards the big idea. It shows aspects of the overall scientific model but does not tell us how concepts build on each other. For example, one may consider explaining the phases of the moon to be most appropriately taught after students understand the reason for the day/night cycle (at its simplest, why we see the sun during the day and not the night). But should the phases of the moon be considered to represent a more sophisticated level of understanding than that of day/night? The underlying conceptual model applied to explain the phases of the moon is more complex than that for the day/night cycle, since fully explaining the phases of the moon requires understanding of the earth's rotation and the moon's orbit. The day/night cycle is also part of a larger phenomenon: the daily motion of all celestial objects is caused by the earth's rotation (including the sun, moon, stars, planets, etc.). This more detailed use of the earth's rotation is not necessary for explaining the phases of the moon and forms its own separate and complete conceptual area. Students could learn to explain the phases of the moon independent of learning to explain the stars' daily apparent celestial motion. Understanding the phases of the moon requires understanding how the earth's rotation explains our daily observations of the sun and moon, and therefore it builds on the day/night cycle level of understanding, but does not require understanding all aspects of daily celestial motion. It also requires understanding how the moon's orbit contributes to our observations making understanding the phases of the moon more than just a more sophisticated way of knowing the day/night cycle.

Given the nature of the celestial motion big idea, a possible solution for addressing these complexities is to use Wilson's (2009) proposal to build learning progressions from sets of *construct maps*. Each construct map focuses on a separate astronomical phenomenon, which allows us to focus on a single set of earth-based observations and their associated explanatory motions (e.g., daily apparent celestial motion and the rotation of the earth). Construct maps can be stacked or aligned to create a full learning progression leading towards a single big idea that students may reach with appropriate instruction. Figure 1 shows a potential mapping of individual construct maps connected within a single learning progression for celestial motion, including earth-based observable phenomena and associated explanations in the heliocentric frame of reference. Along the left-hand side of the diagram are the explanatory motions for each phenomenon (descriptions of what is actually happening in the solar system). Some explanatory motions of celestial objects correspond to multiple phenomena such as rotation of the earth and orbit of the earth. This is shown by the grey shaded bands in Figure 1. Other explanatory motions only appear in only a single construct map such as orbit of the moon or the orbit of the planets. This is just a rough sketch of the layout of the construct maps, not a completely articulated or validated learning progression; this representation does not show the intermediate levels or all of the necessary links between the construct maps. However, it does provide a potential structure for future research. The difference in height of the columns in Figure 1 may represent differences in difficulty of achieving a scientific understanding of that construct. For example, it seems likely that learning to explain the seasons is more difficulty than learning to explain the phases of the moon. However, there is limited empirical data to validate this hypothesis. A more pragmatic explanation for the differences in heights of the columns is that this made it easier to show how the explanatory motions connect to each construct map.

In this representation, learning progresses upward through levels of increasing sophistication with lower levels of each construct map representing the naïve ways of knowing as students enter instruction. Higher levels of each construct map represent increasingly sophisticated understanding of how to use the actual motions of celestial objects to provide aspects of the scientific explanation for an earth-based observable phenomenon. A full and rich understanding of celestial motion occurs as students explore connections between the different construct maps so that they see celestial motion as not just a collection of phenomena but as part of a larger pattern of motions. Instruction can begin along any of the construct maps in Figure 1, although future research may find that some starting points may be more fruitful for learners than others.

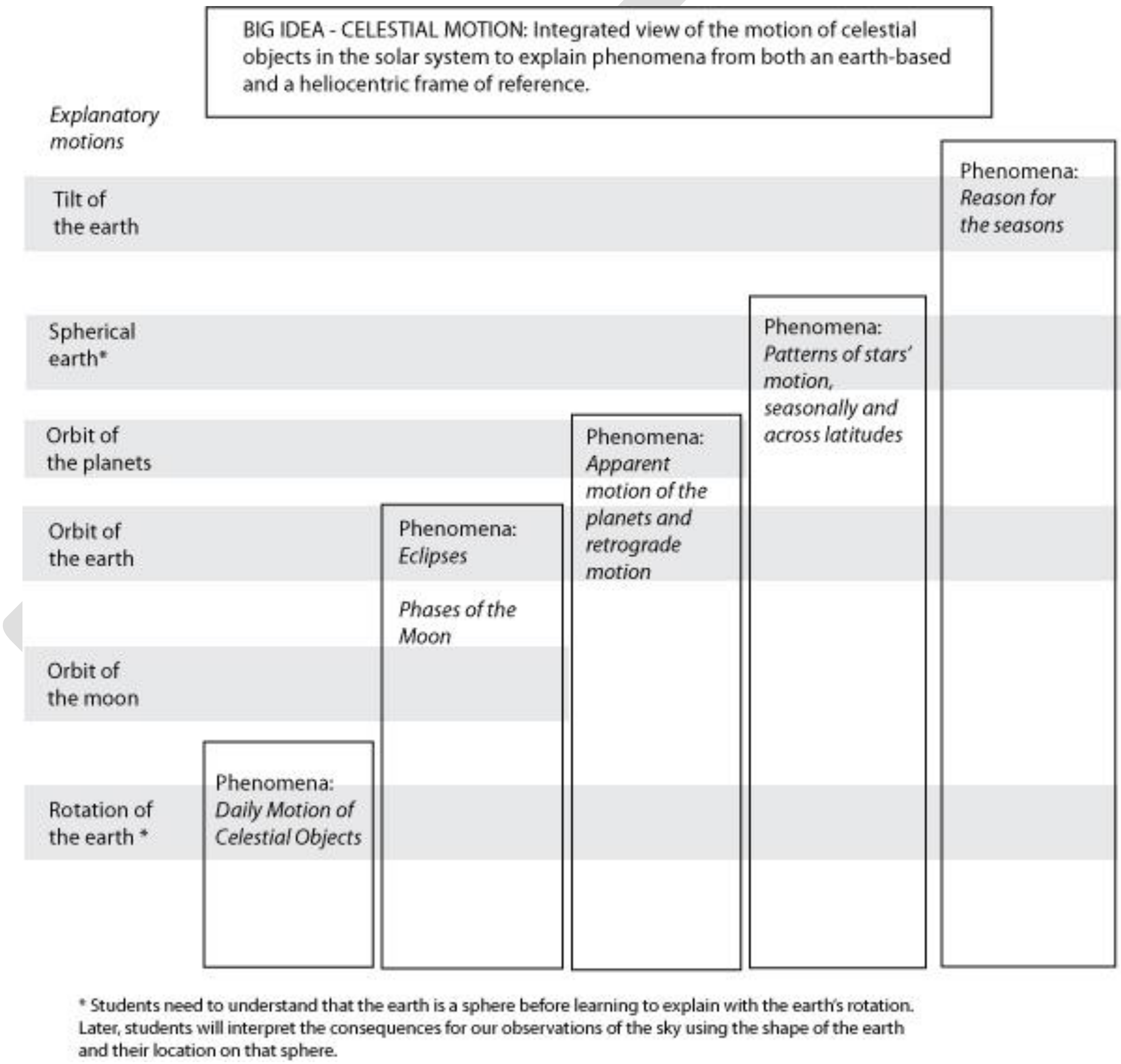

Figure 1. An outline of how earth-based phenomena and the actual heliocentric motions within the solar system can be linked within a learning progression for celestial motion. Each of the five vertical columns are construct maps. The grey shaded bands indicate where explanatory motions

(left column) link to each of the construct maps. For example, the grey band from the rotation of the earth overlaps all of the construct maps because it is part of the explanation for all of the phenomena.

Challenge #3: Accounting for both the earth-based perspective (observable phenomena) and the heliocentric model (explanatory motion)

A third challenge arises as we consider the importance of both the *observational phenomena* in the earth-based frame of reference and underlying *explanatory motion* in the heliocentric frame of reference. Merely understanding that the earth rotates, that the moon orbits, that the earth orbits the sun, that the earth is tilted, etc. is not enough to use these motions to explain earth-based observations. For example, elementary students may be able to state that the earth rotates and demonstrate that concept with a model. But when asked to explain why the sun rises and sets, they do not use the earth's rotation to explain the phenomenon (Plummer, Wasko, & Slagle, in press). Thus, additional attention must be paid to how students describe the observable phenomena and understand the connection between the evidence (observable phenomena) and the underlying explanatory motion in this domain. In building a learning progression we must determine how to value students' understanding of the apparent celestial motion. For example, consider a student who describes the sun as rising and setting in the same place on the horizon but explains this with an accurate description of the earth's rotation. His description of the earth-based perspective suggests that he is not reasoning between the frames of reference. Is his answer more sophisticated than one offered by another student that includes an accurate description of the sun rising and setting in a smooth arc from east to west across the sky but an explanation that the earth rotates twice a day? Each child has a piece of the scientific model, but neither has a sophisticated understanding of the consequence of the earth's 24-hour rotation on our observations of the sun.

These examples suggest that development of a celestial motion learning progression will need to describe increasing sophistication of both descriptions of earth-based observable phenomena and explanations for those motions. My colleagues and I have been studying children developing sophistication along a portion of the learning progression: the daily celestial motion construct map (the left-most construct map of Figure 1; Plummer, et al., in press). Consistent with the design of other learning progressions, the daily celestial motion construct map (shown in Table 2) is anchored by naïve understanding at one end and the full scientific understanding across both frames of reference at the other end. The construct map is organized around two dimensions. First, I organized students' ideas by their explanation (do they use the earth's rotation or a non-normative explanation?). Within those groupings, I organized the levels by the accuracy of their description of the apparent motion. In doing so, it goes beyond the simple overview provided in Figure 1.

In Table 2, each row describes a level of the construct map and represents progress along the construct, increasing in sophistication from bottom to top[1]. The left-hand column gives an overview of the level. The middle column identifies ways that students might describe the earth-based observation at that level. The right-hand column describes how students explain the earth-based observations at that sub-level. Notice that increases in sophistication result when students pair accurate descriptions with accurate explanations, showing that they are making the link between the two frames of reference. At lower levels, students are not making accurate connections between the frames of reference, but they have adopted aspects of the scientific concept. For example, students might offer non-scientific descriptions of the earth's rotation in their explanation, which is an advance compared to believing the sun actually moves around the earth (a more naïve perspective).

Table 2
Construct Map for Daily Celestial Motion

Levels of the Construct Map	Earth-based observed motions	Explanation for observed motions
Scientific daily celestial motion: Students at the scientific level use the earth's rotation to explain all earth-based observed patterns of daily celestial motion. [NOTE: This level connects, as pre-requisite knowledge, to the *phases the moon* and *patterns of the stars' motion* construct maps.]	Students give an accurate description of the sun, moon, and stars' apparent daily motion by describing all as rising and setting in the same direction.	Students use the earth's rotation to explain all apparent daily motion.
Upper synthetic: Students use the earth's rotation to explain that the sun appears to rise and set across the sky. However, students do not extend this explanation to both the moon and stars.	All students in *upper synthetic* give a scientific description for the apparent motion of the sun. Within this level, there are students who may also give the scientific description for the moon and stars' apparent motion as well.	Students accurately describe the earth's rotation. Students may use the earth's rotation to explain only the sun's apparent motion or they may also explain the moon or stars' apparent motion accurately.
Lower synthetic: Students believe that the sun is stationary and that the earth is moving. Students' descriptions and explanations for the moon and stars' apparent motion are likely to retain the inaccuracies of the naïve perspective; this level is primarily determined by how the	The apparent motion of the sun, moon, and stars may or may not be accurately described	Explanation for sun's apparent motion includes less sophisticated ideas (e.g. the earth orbits the sun once a day) and more sophisticated ideas (e.g., using the earth's rotation in

[1] A more detailed description of the levels is provided in Plummer, et al. (in press).

students explain the sun's apparent motion. There may be limited coherence between the actual motion of the earth and apparent patterns of motion of other celestial objects.		combination with other inaccurate explanations).
Naïve: This level represents where most students enter elementary school. Students at this level believe that the earth-based patterns of motion (or lack of motion) are due to the objects' actual motion (or lack of motion.	Some students may be able to provide relatively accurate descriptions of the sun and moon's apparent motion while others provide only non-scientific descriptions. Most believe that the stars do not move or only move at the end of the night.	Explanations use the sun, moon, and stars' actual motion.

Challenge #4: Making links to other learning progressions

A fourth challenge in designing a meaningful learning progression is taking into consideration students' understanding of related concepts necessary for full understanding of the targeted content and how these related concepts fit within a learning progression framework. Connections between big ideas should be made explicit as we move forward so that learning progressions can be useful to curriculum developers, assessment designers, and policy makers. One of the major critiques of K-12 school instruction is that students are not forming deep and rich connections across science topics (Corcoran, et al., 2009; Kesidou & Roseman, 2002; Schmidt, McKnight, & Raizen, 1997). Connections within and between disciplines is one of the differences between a novice and an expert; integrated knowledge allows for flexible retrieval of information to be used in problem solving situations (NRC, 1999).

Full understanding of celestial motion requires understanding of related big ideas. Several areas associated with the big idea of celestial motion could potentially be developed as separate learning progressions, including size and scale, light and energy, spatial reasoning, and the process of scientific modeling (which is articulated in a learning progression by Schwarz, Reiser, Acher, Kenyon, & Fortus, this volume). At lower levels, understanding of the size and distance to celestial objects is important for learning about daily celestial motion. Shifting from a naïve perspective (the sun and moon move around the stationary earth while the stars stay still) to the scientific perspective (the earth rotates once a day causing the relatively stationary sun and stars and the slow moving moon to appear to rise and set) is assisted by students learning that the sun is very large and very far away compared to the earth and that the stars are similarly large but much farther away. The moon's size and distance from the earth also becomes useful in understanding why the moon slowly orbits the earth and contributes to understanding the difference between phases of the moon and eclipses. Knowledge of the properties of light becomes important as students progress to more advanced topics of astronomy. For example, understanding the phases of the moon requires that students understand that the moon appears to be lit by sunlight that is reflected off of the moon's surface which then travels in a straight line to reach our eyes. These examples demonstrate that building sophistication across a domain such as astronomy means that students are learning both to apply more sophisticated motions of celestial objects to observable phenomena and to make connections to other concepts in order to construct full explanations.

Ultimately, moving to more sophisticated levels of astronomy than are expressed in the five construct maps (daily celestial motion, phases of the moon, planetary apparent motion, stellar apparent motion, and the reason for the seasons; Figure 1) will involve integration with big ideas in physics, such as gravity. For example, the celestial motion learning progression leads towards explanations of earth-based observations of the sun, moon, stars, and planets' apparent motions; explaining why the planets and moon orbit in the ways that they do, as well as how those orbits first began (the formation of the solar system) requires the use of gravitational theory. If learning progressions are developed in ways that utilize structures similar to the interconnected construct maps approach (Wilson, 2009), then perhaps making links between learning progressions will be a matter of finding alignments between segments of the concept maps which comprise the larger learning progressions.

Obtaining Theoretical and Empirical Support for Defining the Learning Progression

Learning progressions are not natural or developmental progressions of understanding; they describe what might be attained through appropriate instruction. After unpacking the concepts through a domain analysis, development of a learning progression relies on what research tells us are potentially productive pathways between naïve and scientific levels of understanding. We can draw on existing literature describing students' alternative conceptions about celestial motion to help define the entry points, what students believe as they enter school. Cross-sectional research may tell us about likely progressions of concepts based on traditional instruction. To go further, design-based research is needed to test potential pathways which result from instruction designed to support students' movement along the progression. This may allow us to identify productive instructional sequences towards the upper anchor. By examining the existing literature, we can uncover the ways in which that literature can help us determine productive sequences and where additional research is needed to provide a comprehensive, multi-year understanding of what progress towards the big idea looks like. In this section, I discuss the challenges presented by limits of the existing literature base in celestial motion and my research group's attempts to extend the research in these areas. This leads to a discussion of challenges researchers face in investigating how students may reach the upper level of sophistication of the learning progression, specifically in terms of the inclusion of astronomy in school curricula and upper level students' lack of foundational knowledge of astronomy.

Challenge #5: Using the Existing Literature Base

In this section, I provide a discussion of literature that helps us understand the naïve level of understanding held by students as they enter formal instruction on astronomy, as well as potential research-based pathways along the construct maps within the celestial motion learning progression. This discussion also highlights areas where additional research is needed to overcome challenges in defining a hypothetical learning progression through the use of existing literature.

Extensive research has been conducted on children's naïve beliefs as they enter school, especially with respect to the shape of the earth and the reason for the day/night cycle (see review by Lelliott & Rollnick, 2010). For example, several researchers have described and refined a developmental progression of understanding the earth's shape and its role in children's own personal cosmologies, which begins with the common belief that the earth is flat and objects fall universally "down" (e.g. Nussbaum & Novak, 1976; Nussbaum & Sharoni-Dagan, 1983; Sneider & Pulos, 1983; Vosniadou & Brewer, 1992). Research on children's explanations for the day/night cycle demonstrates that children begin school believing day and night are caused by the sun's actual motion or objects blocking the sun (Samarapungavan, Vosniadou, & Brewer, 1996; Vosniadou & Brewer 1994). Research on the phases of the moon suggests that many early elementary students believe that the phases of the moon are caused by the clouds, while older students commonly believe phases are caused by the earth's shadow blocking the moon (Baxter, 1989). Literature on students' conceptions has also examined various topics associated with celestial motion, such as aspects of the seasons (e.g. Baxter, 1989), the solar system (e.g. Sharp, 1996), and the nature of the stars (e.g. Agan, 2004). This research on students' early cognition in astronomy provides opportunities to understand the lower levels of the learning progression; however, validating a learning progression which includes the upper levels of sophistication requires understanding the role of targeted instruction in improving student understanding.

In astronomy education, research on the impact of instruction is limited (Bailey & Slater, 2003). Most of the extensive body of astronomy education research has focused on students' and teachers' knowledge of concepts and their mental models (Lelliott & Rollnick, 2010); there have been few longitudinal studies and little focus on the impact of instruction or on connections between the learning of various astronomical concepts and how concepts can be built upon over time. Past studies have also often been limited by focusing on single concepts rather than looking at how students develop an integrated understanding of astronomical phenomena. While there has been more research on astronomy instruction in recent years (Kavanagh, 2007), much is left to be done.

Despite these limitations, astronomy education research does provide some findings related to learning the phases of the moon and the seasons, which can be used to inform development of a learning progression for celestial motion. While learning to describe the observable pattern of the phases of the moon is relatively straight-forward for children, using the relative positions and movements in the sun-earth-moon system to explain these phases is challenging to learners at all ages (Lelliott & Rollnick, 2010). Early elementary students can learn to describe and illustrate the phases of the moon, and there is no indication of specific pre-requisite knowledge needed for learning this pattern (Hobson, Trundle, & Sackes, 2010; Trundle, Atwood, & Christopher, 2007). In a study of students in a New Zealand intermediate school, instruction was designed to promote the development of a scientific mental model of the sun-earth-moon system by allowing students to offer their own prior knowledge and then critiquing the teacher's use of a physical model (Taylor, Barker, & Jones, 2003). While 90% of the students were able to accurately describe the orbital motion of the moon and earth, only 15% could accurately explain the phases of the moon. This suggests that lunar phases are challenging enough that awareness of the actual motions (such as the earth's rotation and moon's orbit) is not enough for students to construct a scientific explanation by themselves or with minimal instruction. Other studies suggest that increased sophistication in students' explanations for lunar phases requires support in describing the observable pattern of change in the phases followed by instruction that directly engages students in generating explanations, using either physical models or computer simulations (Barnett & Morran, 2002; Trundle, et al., 2007; Trundle, Atwood, Christopher, & Sackes, 2010). However, existing research has yet to demonstrate how prior understanding of the earth's rotation or the size and scale of the sun-earth-moon system impacts students' ability to learn the explanation for the phases of the moon.

Seasonal change is another key phenomenon of celestial motion. Extensive research has demonstrated that most people cannot accurately explain the seasons; the most common non-normative explanation is that the earth is moving closer to and farther from the sun (e.g. Atwood & Atwood, 1996; Baxter, 1989; Kikas, 1998; Schoon, 1995; Sharp, 1996). In addition, a lack of understanding that the sun's apparent daily path changes across the seasons (Plummer, 2009a) and a non-normative belief that the earth's orbit is highly elliptical (Kikas, 1998; Schneps & Sadler, 1988) contribute to the difficulty that children have in learning to explain the seasons. Recent studies have documented successful instructional approaches for teaching the reason for the seasons (Hsu, 2008; Slater, Morrow, & Slater, 2008; Tsai & Chang, 2005). However, these studies give a limited explanation of how students understand the seasons from both an earth-based perspective and a heliocentric perspective. They also do not address how pre-requisite knowledge might influence students' learning of this challenging concept and how understanding of this concept might be influenced by other aspects of the celestial motion big idea.

While a significant amount of research has explored instruction related to the seasons and the phases of the moon, research on instruction related to other phenomena associated with celestial motion is relatively limited. Only a few studies have analyzed children's knowledge of motions of the solar system as a whole (e.g. Sharp, 1996; Treagust & Smith, 1989). A study by Sharp and Kuerbis (2006) is perhaps the only example in which instruction on motion in the solar system is investigated. Students showed improvement in describing the motions of planets in the solar system. However, students were not assessed on their use of these actual motions to explain observable phenomena. Research on the impact of instruction related to the apparent motion of the stars, as well as their size and distance, is also limited. A few studies have examined children's explanations for the daily motion of the stars (Baxter & Preece, 2000; Dove, 2002), but limited work has gone beyond this to describe how students learn to explain more advanced aspects of the stars' apparent motion, such as seasonal changes or how apparent motion changes based on one's location on earth.

Understanding and using celestial motion requires spatial abilities: mental rotation, spatial perception, and spatial visualization (Black, 2005; Linn & Petersen, 1985; Wilhelm, 2009). Although a few researchers have begun to investigate the importance of spatial reasoning in instructional-based studies of celestial motion (Sherrod & Wilhelm, 2009; Wilhelm, 2009), much is left to be done as this research only addressed the phases of the moon. Finally, one of the major concepts embedded in learning about celestial motion is size and scale. While several studies have investigated students' ability to make comparisons of relative sizes and distances of celestial objects (e.g. Agan, 2004; Bakas & Mikropoulos, 2003; Sharp, 1996), few studies have reported attempts to teach astronomical size and scale and to build on these concepts to achieve understanding of celestial motion. One exception is a study examining the "Powers of Ten" video (http://powersof10.com) that has been shown to increase the accuracy of students' use of relative size and ability to match objects to their actual metric sizes (Jones, Taylor, Minogue, Broadwell, Wiebe, & Carter, 2006).

The literature described above, and other examples from astronomy education research, has primarily focused on individual features of the celestial motion conceptual domain rather than looking across students' understanding of multiple aspects. Few studies include longitudinal data that would allow us to investigate improvement in these connections across time (Briggs, Alonzo, Schwab, & Wilson, 2006). It is these connections across the associated phenomena that are necessary to define and validate the learning progression so that it is more than an unpacking of the domain. Further, understanding how and why students develop in sophistication along the learning progression and between the construct maps includes describing the role of successful instructional practices. There is limited research showing pathways from children's initial understanding of apparent celestial motion to a fully articulated model of celestial motion. Further, there is limited research on instruction that helps students connect earth-based descriptions of phenomena to explanatory motions. Children are not often asked to compare different frames of reference; when observable phenomena are addressed in research on instruction, studies do not often address how students use celestial motion to predict and explain observations. Because of the limited research on using instruction to develop integrated knowledge of celestial motion phenomena, design and validation of this learning progression will require multiple studies across many grade levels and instructional conditions.

Moving the Agenda Forward with Learning Progression-Based Research

My colleagues and I have begun to conduct research that fills in a few of the gaps in the literature on celestial motion in order to move towards a more comprehensive learning progression. The goals of this work are to investigate a) how students learn to move between frames of reference, b) how instruction can build in sophistication upwards on the progression, and c) how instruction supports connections across constructs within the progression (between phenomena). Below, I will present examples of two approaches I have taken towards defining the levels within the celestial motion big idea for the daily celestial motion and the seasons construct maps.

Daily Celestial Motion

Because of the limited research on children's ability to describe observed phenomena from the earth-based perspective, the first set of studies I conducted was designed to improve our understanding of children's descriptions of the apparent motion of celestial objects (Plummer, 2009a, 2009b; Plummer & Krajcik, 2010). These studies were undertaken to a) provide a portion of the lower anchor for the learning progression, b) offer cross-sectional data to illuminate the ways in which traditional instruction and experiences with the world influence students' initial ideas, and c) investigate the impact of a targeted intervention on students' understanding of the earth-based perspective.

Learning to describe celestial motion from an earth-based perspective is just the first step in improving understanding with respect to the learning progression. Sophistication increases as students learn to explain their observations in the earth-based frame of reference with the actual motions of celestial objects (Plummer, et al., in press). To understand daily celestial motion from both frames of reference (the left-most construct map in Figure 1), we hypothesize that children need to a) experience visual and/or kinesthetic descriptions of the apparent patterns that are then explicitly connected to explanations that use the earth's rotation and b) confront the common non-normative use of the moon's orbit to explain the moon's daily apparent motion. Building on these ideas, my colleagues and I have used a design-based approach towards instruction that supports children in moving between frames of reference. We started with a small group of gifted 3rd grade students in a pilot study (N=16; Plummer, et al., in press). The results support our hypothesis that movement along the construct map is can be accomplished by instruction that combines visual and kinesthetic instruction, along with the previously described methods for learning the apparent motions.

Building on these results, we have begun to analyze the results of integrating these strategies into the regular 3rd grade astronomy curriculum in a suburban school district (N = 100; Plummer, Kocareli & Slagle, 2010). To understand the nature of student improvement with instruction, we analyzed outcomes of four instructional conditions that varied the level and type of instructional support provided to the students. Analysis of the nature of improvement from each of the four conditions suggests that children who experience instruction that focuses primarily on heliocentric motions (rotation of the earth, orbit of the moon, etc.) show limited improvement in their understanding of the earth-based frame of reference and similarly, only focusing on the earth-based perspective does not allow students to automatically connect those observations to the earth's rotation. We analyzed the ways in which students' understanding changed and improved based on their instructional condition, examining frequencies in the transitions student made from pre- to post-instruction to identify aspects of daily celestial motion that appeared to be pre-requisite to more sophisticated levels of understanding across many of the students. This analysis supports our hypothesis that understanding how the earth's rotation explains the sun's apparent motion is an important intermediate level towards more sophisticated understandings, such as explaining the moon or the stars' apparent celestial motion.

The next step in defining and validating the learning progression is to look for ways that students combine aspects of celestial motion to explain more advanced phenomena (looking both horizontally and vertically in the learning progression in Figure 1). The construct map for daily celestial motion (Table 2) describes increasing sophistication in the use of the Earth's rotation to explain observable phenomena. This daily celestial motion construct map connects to each of the other construct maps in the learning progression as the earth's rotation is part of the explanation for other phenomena. However, full understanding of daily celestial motion is not a precursor to the other constructs; rather, aspects of daily celestial motion link to the other construct maps as prerequisite knowledge. Figure 2 shows these links between the daily celestial motion construct map and the other celestial motion construct maps. For example, a full understanding of lunar phases and eclipses includes understanding how the earth's rotation causes the moon's daily pattern of motion and the helps explain the correlation between the moon's appearance and the time that it rises and sets. Understanding the daily celestial motion of the moon also helps students distinguish between the scientific explanation for the phases and a common misconception that they are caused by the earth's rotation (Trundle et al., 2010). Part of our continued analysis will be to investigate this connection in terms of the patterns of improvement observed in the third grade student data.

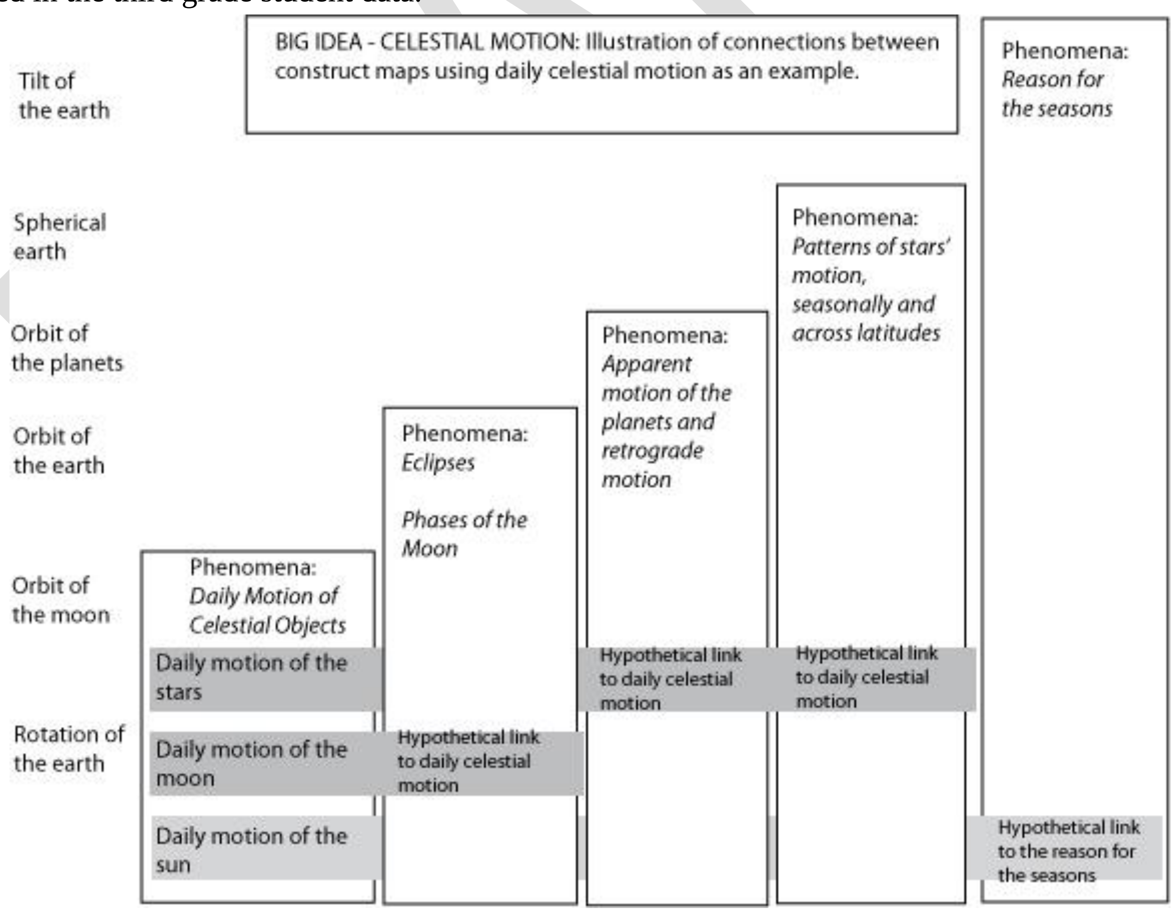

Figure 2. Aspects of daily celestial motion are pre-requisite to explaining more advanced concepts. Knowledge of the daily motion of the sun is part of explaining the seasons. The daily motion of the moon is part of to a full understanding of the lunar phases and eclipses. The daily motion of the stars is part of a full understanding of the stars and planets apparent motion across time.

Reason for the Seasons

My colleague and I have also begun to investigate older students' explanations for how patterns in the sun's apparent motion cause the seasons, building on our understanding of children learning to explain daily celestial motion (Plummer & Agan, 2010). This study examined eighth grade students learning both patterns associated with an earth-based perspective and the explanation for those patterns. Using an IRT approach, we identified a potential ordering of concepts relating to the seasons, from least to most difficult. Based on this quantitative analysis, a set of levels describing increases in sophistication were identified to define a construct map for the seasons. We further refined the construct map by using the tentative levels from the IRT analysis as a tool to classify specific students' knowledge. To do so, we considered how higher levels of the construct map built on previous levels, refining the levels using a Guttman scale approach (assuming that understandings at a given level include those in the previous levels). Individual students were assigned to the levels identified using the IRT analysis based on their responses to the assessment. This analysis revealed that students may reach–intermediate levels of the learning progression without being able to accurately explain the sun's daily motion, leading us to tentatively link the Daily Celestial Motion construct map to the Reason for the Seasons construct map at the *scientific* level; this is in contrast to our initial analysis, which had suggested this link would appear at a lower level of the construct map. However, this is a tentative description and additional research is needed to test and validate the construct map.

Very few students reached the scientific level of the progression. This may be, in part, because many students had not achieved a robust mental model of the sun-earth portion of the daily celestial motion construct map, a pre-requisite for the top level of the seasons construct map. Without a full understanding of the sun's apparent motion, many students did not have the appropriate foundational knowledge for advancing to more complex concepts within the seasons construct map (Plummer & Agan, 2010). Another possible explanation for the low percentage of students reaching the scientific level was the amount of classroom instruction; one day, out of the 10-day curriculum, was spent integrating the students' observational knowledge with the tilt-model used to explain the seasons. It may be that more students would have reached the scientific level if additional time and guidance had been provided, allowing them to further develop explanations for the seasons. The research described here would be strengthened by testing the construct maps with students in different contexts. This can include exploring learning pathways across different cultures, as well as understanding the role of geographic location and local temperature patterns in developing understanding of celestial motion.

Challenge #6: Obtaining Empirical Support for Hypothetical Learning Progressions

The research my colleagues and I have carried out reveals an additional challenge in obtaining empirical support to validate the celestial motion learning progression. Significant research has shown that many, if not most, children and adults do not have the foundational knowledge – those concepts that form the initial levels of the construct maps– needed to support more sophisticated levels of understanding (e.g. Atwood & Atwood, 1995; Baxter, 1989; Mant & Summers, 1993; Brunsell & Marcks, 2005; Plummer, 2009a; Plummer & Agan, 2010; Plummer, Zahm, & Rice, 2010; Schoon, 1995; Sharp, 1996; Trumper, 2006). This lack of foundational knowledge of astronomy means that for older students, we will not be able to begin instruction at some of the more intermediate levels of the progression; advancing to the scientific levels will require starting with some of the more elementary concepts of astronomy (daily patterns of motion and the earth's rotation as an explanation for those patterns, for example). While students in our study showed overall improvement in their understanding of the seasons, their learning may have been hindered by their lack of important fundamental knowledge (Plummer & Agan, 2010). This suggests that, for many teachers, reaching the goal end of the learning progression may mean teaching all of the foundational concepts as well -- at least until school curricula are designed to address these foundations sufficiently at younger grades. This will be a problem for testing and validating additional aspects of a celestial motion learning progression because of the time involved helping students reach more advanced levels from their naïve level of understanding. More time and effort could be put into moving them to more advanced levels of astronomy if they entered the instructional setting with at least some foundational knowledge of celestial motion.

Part of the explanation for students' lack of foundational knowledge is that coverage of astronomy is limited across K-12 schooling. While I have been unable to find studies directly measuring the coverage of astronomy at the elementary level, research suggests that many students are not studying astronomy in middle or high school (Plummer & Zahm, 2010). This limits the research community's ability to test theories in the context of classroom-based instruction. Secondary schools that do include astronomy often do so in very short time frames (Plummer & Zahm, 2010). If students do not have the foundational concepts from elementary school, the fast-paced coverage in secondary schools will be unlikely to result in a scientific understanding of the target concepts.

What are potential solutions to the challenge to obtaining empirical support? First, we may include the importance of pre-assessment of foundational concepts in how we articulate learning progressions. This will include emphasizing that learning progressions do not describe students' knowledge at particular grades, but instead that these progressions describe intermediate steps that can be accomplished through well-crafted instruction. In other words, it is important to emphasize that the progress is not inevitable and that instruction at higher levels of the learning progression should not proceed unless students have acquired the necessary foundational knowledge (from lower levels of the progression). Second, researchers will need to identify school districts with clear plans to provide multiple opportunities for students to study astronomy with increased sophistication. This would allow research to explore how students develop sophistication in astronomy through repeated explorations of these concepts and potentially lead to longitudinal studies which could provide evidence for validating learning progressions. Reform-based curriculum developed using research-based findings about teachers' pedagogical content knowledge and common alternative conceptions in astronomy, along with a clear plan to support teachers through professional development would also be required. Examples of schools or districts which demonstrate the success of instruction based on a learning progression may help make the case for other districts to move in this direction.

Conclusions

In this chapter, I have presented initial research conducted to define a learning progression in astronomy and have articulated several challenges: the first set is associated with identifying the focus and the second set with obtaining support for defining the learning progression. The solutions presented to these challenges may be of use to researchers developing learning progressions around other big ideas of science. Other researchers may consider the benefits of using construct maps to organize smaller elements of their learning progressions. This could be done to describe how students learn various phenomena or to demonstrate ways that learning can occur along different pathways, both of which occur in the celestial motion learning progression. It may also be a useful organizational tool as learning progression researchers consider ways to define learning progressions across both content and scientific reasoning abilities, such as in Songer, Kelcey, and Gotwals' (2009) complex reasoning in biodiversity learning progression. The choice to use construct maps, as well as the organization of the construct maps, will depend on the nature of the big idea. A second lesson learned from the challenges discussed here pertains to the connections between learning progressions. This includes identifying ways that concepts are connected between learning progressions (such as the importance of understanding properties of light to celestial motion) as well as connections that could lead to more sophisticated understanding of the big idea (such as extending the celestial motion learning progression to connect to the big idea of gravity). Ultimately, moving to more sophisticated levels of understanding astronomy will require that students deepen their understanding of physics as well as their scientific reasoning skills.

The second set of challenges explored address validating the learning progression. This work is limited by gaps in the current astronomy education research base. While it is clear that much additional research is needed on instruction in this domain, identifying the most appropriate instruction and conditions for testing and validating the learning progression will require extensive effort. For example, while longitudinal studies may help us answer questions about the validity of the learning progression, are such studies possible? Research to define and validate the celestial motion learning progression is difficult because of the nature of astronomy education in schools. Astronomy is often left out of K-12 schools, so finding school-based settings to explore these questions will be difficult (Plummer & Zahm, 2010). Many districts require their teachers to "teach to the test" and/or follow a standard curriculum in step-by-step fashion; other district-level policies may result in limited instructional time devoted to astronomy. Therefore, external pressures will make large scale validation projects a challenge. Limited instructional time challenges us to consider what is considered “good enough” in the context of this big idea and how to communicate trade-offs to teachers, curriculum developers, and policy makers.

The research presented here is an illustration and exploration of the initial steps towards the extensive work that is left to be done on a learning progression for celestial motion. Additional empirical evidence is needed to define and validate the levels of all of the construct maps that make up the celestial motion learning progression. Further, the big idea elaborated here is only one possible approach to learning progression research in this domain. Other big ideas in astronomy, leading to robust knowledge of the domain appropriate to K-12 education, should be explored. This would lead to the definition and validation of additional learning progressions supporting improvement of K-12 astronomy education through the development of more coherent standards and research-based curricula.

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