Development of a learning progression for the formation of the Solar System

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To appear in the *International Journal of Science Education* (March, 2015)

Abstract

This study describes the process of defining a hypothetical learning progression for astronomy around the big idea of *Solar System formation*. At the most sophisticated level, students can explain how the formation process led to the current Solar System by considering how the planets formed from the collapse of a rotating cloud of gas and dust. Development of this learning progression was conducted in two phases. First, we interviewed middle school, high school, and college students (N=44), asking them to describe properties of the current Solar System and to explain how the Solar System was formed. Second, we interviewed 6th grade students (N=24) before and after a 15-week astronomy curriculum designed around the big idea. Our analysis provides evidence for potential levels of sophistication within the hypothetical learning progression, while also revealing common alternative conceptions or areas of limited understanding that could form barriers to progress if not addressed by instruction. For example, many students' understanding of Solar System phenomena was limited by either alternative ideas about gravity or limited application of momentum in their explanations. Few students approached a scientific-level explanation, but their responses revealed possible stepping-stones that could be built upon with appropriate instruction.

Keywords: astronomy; learning progression; secondary education

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Introduction

Recently, there has been an increased focus on organizing student learning in science around big ideas in order to move away from superficial instruction that engages children in ‘mile-wide and inch-deep’ curriculum. Science instruction should help students develop deeper understanding of an integrated framework of scientific knowledge. There is a consensus in the U.S. that learning progression (LP) research has the potential to help change the way we address science in K-12 education, by guiding the development of research-based standards and curricula that support students’ development of conceptual understanding around big ideas of science (e.g. Corcoran, Mosher, & Rogat, 2009; Krajcik, Sutherland, Drago, & Merritt, 2012; NRC, 2012). This is supported by the *Framework for K-12 Science Education* (*Framework;* National Research Council [NRC], 2012) which suggests that ‘[to] develop a thorough understanding of scientific explanations of the world, students need sustained opportunities to work with and develop the underlying ideas and to appreciate those ideas’ interconnections over a period of years rather than weeks or months… learning progressions provide a map of the routes that can be taken to reach that destination’ (p. 26). Yet, LPs have yet to be empirically developed for many big ideas.

We have begun the process of taking a closer look at one of these big ideas: how the history of the Solar System can be determined through observations of objects and structures in their present state, along with application of physics and chemistry principles. What follows is a brief description of the big idea, clarifying our goal for student learning and as a contrast for our later discussion of student ideas in this domain. The Solar System began forming when a large cloud of gas and dust collapsed due to the force of gravity. The cloud had an initial angular momentum, and as it collapsed, it became denser and rotated faster. The accumulated mass and pressure at the centre became great enough to form a star, our Sun; material that collapsed into a disk around the Sun collided, stuck together, and grew into planets. The formation model explains observations of the current Solar System: the differences in planet composition, the relative flatness of the Solar System, and the motions of the planets and other objects. By focusing on the formation model, we can help teachers and students attend to features of the Solar System that are explained by the same theory, while moving away from rote memorization of 'planet facts.'

The Solar System and its formation is important to the science curriculum because it provides a new context in which students can apply understanding of mathematical relations as well as physics principles, such as gravity and angular momentum. It provides an opportunity for students to learn about cross-cutting ideas of science such as deep time, size and scale, and frames of reference. Further, engagement with astronomy topics is widely suggested as a method of inspiring students to further study of science and technology (e.g. International Astronomical Union, 2012). This big idea appears in standards and curricula across international contexts, indicating that this central aspect of astronomy is widely recognized. In the U.S., the Framework includes the Solar System and its formation as one of the big idea targeted by newly developed science standards (NRC, 2012). The Chilean K-12 curriculum recommends students learn about Newton's and Kepler's laws while also considering evidence regarding the origin and evolution of the Solar System (Gobierno de Chile Ministerio de Educación, n.d.). Understanding the Solar System is also featured in the National Curriculum of England, as well (Department for Education, 2013). Research on students and teachers learning about the Solar System in Brazil (Colombo, Aroca, & Silva, 2010), the Netherlands (Henze, Van

Driel, & Verloop, 2008), England (Sharp & Kuerbis, 2005), and Japan (Suzuki, 1998) suggests these ideas are important across cultural contexts.

However, as we will discuss further below, there is limited research into how students develop sophisticated understanding of the current Solar System or how its history shaped its current appearance. The literature includes a close examination of student thinking around certain elements of this big idea, such as the nature of gravity (e.g. Williamson & Willoughby, 2012) and planetary orbits (e.g. Yu, Sahami, and Denn, 2010), without considering how these ideas fit together as part of a coherent big idea or characterizing student thinking as a progression of increasingly sophisticated versions of the scientific concept. Thus, we began investigating the challenges students face in this domain, through an analysis of student interviews and the structure of the scientific discipline, to answer the following research question: How can we describe successive levels of sophistication in student thinking about the Solar System and its formation using a learning progression framework? This will allow us to develop a framework that can guide future research on how to design instruction that supports student progress in learning about the Solar System and its formation.

Students' Understanding of the Solar System and its Formation

Few studies have examined students' ideas about the composition of the planets or how they formed. Hansen and colleagues (2004) compared a virtual reality-based course to a traditional astronomy course on US undergraduates' understanding of planet compositions. Students in the traditional course could provide a more complete explanation of the difference between rocky and gaseous planets' compositions. The authors suggest that the 3D modelling in the virtual setting may have distracted students from learning the more factually-based information. Sharp (1996) found that 10- to 11-year-old English children believe that the Solar

System is thousands to millions of years old or that it had always existed. The students provided a variety of explanations for the Solar System's formation, including that the Solar System was formed during the Big Bang and the more normative view that there was an accretion-like process of rocks joining together to form the planets. Other researchers have studied students' ideas about the related topic of star formation. Agan (2004) found that some students believe stars form through collisions, while others understand that the process involves gravity and occurs in nebulae. Bailey and colleagues (2009) found that, prior to instruction, US undergraduate students rarely provide a complete explanation for star formation. While about half the students described material coming together to form stars, only a small portion (16%) suggested this was due to gravitational collapse.

More research has examined students' understanding of the motion of Solar System objects. Sharp (1996) also reported on students' descriptions of how objects move in the Solar System; students ranged from not knowing about planetary orbits to describing those orbits with varying degrees of accuracy; some students believed that planets do not move because there is no gravity in space. Sharp and Kuerbis (2006) investigated 9- to 11-year-old English children's ideas after a unit focused on Solar System astronomy. Students' understanding shifted from random organization of Solar System objects, with random motions, to the heliocentric view of the planets orbiting in the same direction on roughly the same plane around the Sun. Before instruction, students occasionally used the Sun's gravitational pull to explain orbits, but after instruction this idea was far more prevalent.

Research with older students has focused more on how students explain the cause of planetary orbits. Yu, Sahami, and Denn (2010)'s study of US college students' explanations for planetary orbits found that 45% understood that gravity is responsible for the motion of the planets, though not all mentioned this was due to the Sun's gravity. Other students used additional factors to explain planetary motion, such as density, magnetic fields, or number of moons. However, the authors did not indicate whether any of the students understood that orbits are a combination of the gravitational force between a planet and the Sun and the planet's tangential velocity. Velentzas and Halkia (2013) engaged Greek high school students in a thought experiment about Newton's Cannon to help them learn that an object fired with sufficient initial velocity from a cannon will take up orbit around the Earth. Most students initially found it difficult to accept that a projectile with a trajectory that curves to match the Earth's curvature will orbit the Earth; with discussion of scenarios, most students' understanding shifted towards the normative explanation. The authors suggest their difficulty arose because the thought experiment conflicted with their everyday experiences.

Explaining the planets' orbital motion and the formation of the Solar System requires an understanding of gravity. Kavanagh and Sneider (2007) reviewed research literature surveying students, across age groups, about gravity and objects' motion in space. Several ideas consistently appeared across the different studies: "many students believe that air is needed for gravity to act. This misconception leads to the further misunderstanding that gravitational attraction rapidly diminishes with an increase in altitude until there is none at all in space" (p. 24). Treagust and Smith (1989) examined Australian high school students' ideas about the relationship between gravity and planetary motion. Students indicated several alternative ideas about gravity, including that a planet's gravity is related to its distance from the Sun and the speed at which it rotates. Williamson and Willoughby (2012) also investigated US college students' mental models of gravity. A frequently observed mental model was the *boundary model*, in which a boundary, such as the surface of a planet, the edge of the atmosphere, or an orbit, represents the end of gravity's influence. Students with the *orbital indicator model* may think that a satellite's orbit about a planet can indicate the strength of the planet's surface gravity. The *mixing of forces model* occurs when students confound gravity with other forces, such as magnetism, rotation, or atmospheric pressure. Williamson and Willoughby also identified ways the college students were inaccurately using elements of the scientific model, such as the idea that only heavy objects can gravitationally interact or that density, rather than mass, determines gravitational force.

These studies provide some initial ideas about students' understanding of the Solar System; however, much additional study is needed to characterize students' understanding of the Solar System and its formation as a progression of increasingly sophisticated ideas. More research is needed about how students conceptualize the use of physical properties (e.g. planet composition) to organize objects in the Solar System. Additional research is also needed that examines how students develop explanations for planetary orbits, in ways that explicitly examine their understanding of the role of inertia in addition to the force of gravity. Then, to build towards the big idea connecting the current Solar System to its formation, more research is needed that considers how students' understanding of formation model may point them towards the first steps in explaining the current physical and dynamic properties of objects in the Solar System. This includes considering how students apply their understanding of gravity to explain the accretion of planets in the early Solar System and, in combination with angular momentum, explain how planets came to be in similar orbits on approximately the same plane.

Learning Progression Framework

Using an LP framework allows us to emphasize the development of conceptual goals building over time towards a big idea as key ideas are linked together in a web-like fashion

(Corcoran et al., 2009; Krajcik et al., 2012). LPs describe how students may grow in sophistication towards a big idea in science (Corcoran et al., 2009). These big ideas describe unifying concepts that help make sense of a broad variety of phenomena, offering robust explanatory power for the world around us (Smith et al., 2006). A LP describes how intermediate levels of sophistication can be valued and built upon by instruction across many grades, rather than only comparing alternative ideas and scientific ideas. LPs are viewed as *hypothetical* models of learning as they describe 'the typical levels that students' understanding might be expected to go through given instructional exposure' appropriate to the phenomena and experiences needed to make progress in their explanations (Rogat, Anderson, Foster, Goldberg, Hicks, et al., 2011, p. 4). There may be multiple paths that students could take to reach the upper levels of sophistication; however, this is likely to be a relatively small set, as pathways are defined by the logic of the discipline, student cognition, and instructional design (Krajcik, 2011).

The development of a LP often begins with unpacking the big idea and reviewing literature on student thinking pertinent to the concepts in the LP (Rogat et al., 2011). From there, the initial LP hypothesis can be further developed either with cross-age samples (e.g. Gunckel, Covitt, Salinas, & Anderson, 2012; Mayes, Forrester, Christus, Peterson, Bonilla, & Yestness, 2013) or in the context of instruction (e.g. Shea & Duncan, 2013; Yin, Tomita, & Shavelson, 2013). Our review of the literature on students' ideas about the Solar System was insufficient for use in developing a full LP. In some cases, the literature provides insight into what alternative ideas students have but without providing enough depth to characterize students' ideas in levels of sophistication (e.g. planetary properties); in other cases, literature is missing on how students conceptualize key elements of the big idea (e.g. the use of inertia in planetary orbit explanations; differentiating microscopic and macroscopic accretion). This led us to conduct cross-age interviews as the first step in an iterative design process towards developing a hypothetical LP.

To accommodate the complexity of the Solar System and its formation, we examined progress across multiple dimensions (physical properties, dynamical properties, formation, and gravity). Students may initially learn these separately, but will eventually need to understand their integration to fully explain the LP's big idea. Wilson (2009) suggests building LPs from multiple *construct maps* in order to address these multi-dimensional LPs. A construct map is similar to a LP in that it possesses an upper anchor (the goal-level understanding set by the discipline and societal expectations), a lower anchor (where students begin as they enter school), and descriptions of increasing sophistication in between. Construct maps differ from LPs as they can be used to describe different dimensions of a big idea. Outlining a LP as a set of interrelated construct maps provides flexibility for an iterative development process by allowing researchers to focus on building a few construct maps around particular grade bands at a time (Plummer & Maynard, 2014).

Methodology

Our LP research team included learning scientists, astronomers, and experienced middle and high school teachers. Development was guided by the 'assessment triangle,' a process of reasoning from evidence towards understanding student thinking (NRC, 2001). The vertices of the assessment triangle are: a *model of cognition* representing how student understanding develops in the domain (in this case, our hypothetical LP), tasks that provide opportunities for *observation* of students' performance, and an *interpretation* method for observations of student performance in relation to the model of cognition. Below, we describe our iterative process of *observing* student performance through semi-structured interviews and *interpreting* the interview data in relation to our developing model of cognition.

The first iteration of the LP development was based on a cross-age study, while the second iteration was based on pre/post interviews with students who participated in a curriculum focused on our big idea. In this paper, we describe our process of developing the Solar System LP.

Participants

Year 1 data collection. Students from middle school (6th grade, 11-12 years old; n=18), high school (9th – 12th grade, 14-18 years old; n=20), and college (n=6) from urban, suburban, and rural locations across Pennsylvania were interviewed (N=44). The middle school students, from multiple districts, were interviewed before their astronomy unit to help us address the lower anchors of the construct maps. High school students were selected from across grade-levels and school districts to capture student thinking after typical experiences learning astronomy in secondary school. The college students were selected from those who had taken a college-level introductory astronomy course to elicit student thinking closer to the upper anchor of the LP. All students who returned consent forms were interviewed.

Year 2 data collection and instructional context. The findings from our first year of data collection informed the development of a week-long professional development (PD) workshop on instruction that would move students towards the big idea of the Solar System and its formation. One participant volunteered to use what she learned in the PD to revise her 6th grade astronomy unit. The 15-week curriculum included both astronomy content relevant to our LP and engagement with other astronomical phenomena. Students learned about how the planets and asteroids orbit the Sun and used observations of these objects in a computer simulation to determine that the Solar System is relatively flat. They investigated how planetary orbits depend on distance from the Sun and initial velocity. The students developed evidence-based arguments for how to group planets based on their properties. Finally, they developed a model for the accretion process of how gas, dust, and ice built up to form the planets and engaged in a whole-class scientific argumentation session to discuss the sequence of events that led to the formation of the Solar System. We interviewed a random sample of the teacher's 6th grade students (keeping an equal number of male and female students) before and after the unit (N=24).

Interview Protocol

An open-ended interview protocol engaged students in describing the current structure and motion of objects in the Solar System, its formation, and gravity. The interview protocol began with students drawing a picture of the Solar System. Small changes were made to the protocol after Year 1 to better capture student thinking along the LP. Some example questions include: *Are there ways to group the planets? Do the planets move or do they stay where they are? Why do they go around the Sun like that? Why don't they shoot off into space? Why don't they crash into the Sun? How did the Solar System form?* All interviews were video and audio recorded for analysis. Interviews lasted about 20-35 minutes. The interview protocol is available upon request.

Analysis

Developing categories and codes. Our analysis began with a top-down process of defining categories representing key aspects of the upper anchors of the four construct maps: physical properties, dynamical properties, Solar System formation, and gravity. The constant-comparative method (Strauss & Corbin, 1998) was used to develop codes within these categories by analysing a cross-age sample of student interviews and then discussing student ideas within our research team. Our unit of analysis was the student's overall understanding of specific concepts. Interview questions prompted students to talk about certain concepts, such as asking the students how they might group the planets. Some concepts came up across answers to multiple questions, such as the formation of the planets or their ideas about gravity. Thus, we looked across each student's entire interview to assign a code to his or her understanding of specific concepts (within categories).

We looked for patterns in how students expressed their ideas about different concepts, within categories we created (e.g. such as *PlanetsComposition* and *PlanetsOrbit*), to develop the initial codes describing the range of student ideas. These initial codes were applied to additional interviews, with new codes added and old codes refined until saturation of codes was reached. Finally, two research team members separately coded a cross-age selection of 10 interviews to establish inter-rater reliability. During this process, we continued to revise our codes. This process was repeated until at least 80% agreement was reached in each category. Our codebook is available in a supplementary document Appendix A at: http://goo.gl/kfXY1F.

Developing and refining the construct maps. Construct map development began by first assigning the relevant categories to their associated construct maps. We then began defining the levels of each construct map by grouping codes that increased in sophistication towards the upper anchor. For example, the gravity construct map levels were defined by groups of codes drawn from four categories (see supplementary Appendix A): *gravity*, *causes gravity*, *extent gravity*, and *gravity strongest*. The upper anchor of each construct map is defined by our goal-level understanding of the scientific concept of each construct map.

Next, we used these tentative definitions of construct map levels to assign students from Year 1 to a construct map level to see whether those combinations of codes were useful descriptions of student thinking. This began an iterative cycle of comparing and revising the construct maps until the descriptions at each level of the construct map were useful at representing the variations in student mental models as measured by our interviews. Next, we compared these initial construct maps to students' ideas from Year 2. This resulted in further revisions across the construct maps as additional data yielded new patterns in how best to group certain ideas into levels.

Solar System Hypothetical Learning Progression

In this section, we present our findings: a hypothetical LP composed of four construct maps, based on an analysis of interviews with students across middle school, high school, and college.

Construct Map 1: Physical Properties of Objects in the Solar System

Students were asked what the objects in the Solar System are made out of and how they might be grouped. Progress through this construct map (Table 1) begins with students developing an understanding of the basic composition of the planets, followed by using composition as a criterion for grouping the planets.

[Insert Table 1 here.

Table 1. Construct map for physical properties of objects in the Solar System]

Students at the lowest level have non-normative ideas about what objects are found in the Solar System, their composition, and how they are grouped. While these students often include some accurate objects in the Solar System, they also include objects that are outside the bounds of the Solar System, the most common being stars, but black holes and the Milky Way were also mentioned.

In defining the levels of this construct map, we allow students to include non-normative objects at Levels 1 through 4 in order to focus more on the promising features of their understanding: the composition and grouping of the planets. Moving up through Levels 2 - 5 involves increasing use of normative descriptions for planet compositions (rocky, gaseous, and/or icy), such as the shift from Level 2 to 3, and using these to group the planets, such as the shift from Level 3 to 4 (see Table 1). For example, Cullen (male, 11th grade) at Level 3 suggested the following about grouping the planets: ‘I think there was three groups, like, the outer ones, the middle ones, and the closer ones.’ When asked what members of the groups had in common, he suggested ‘it might have been the heat and the coldness of the planet and how warm they were. And they were the same colour and like these ones were red and these ones got darker as you got out into the blacks, and purples and blues. [Because of being] so far from the Sun. The light and heat off it.’ We found that across the mid-to-upper levels, some students used productive descriptions to group the planets, such as grouping by distance from the Sun, by temperature, by size, or by mass, while others used less productive groupings, such as by colour.

Students at Levels 4 and 5 group planets by normative descriptions of composition, such as Laney (female, 6th grade), at Level 5:

> *Laney*: The inner planets, they’re the rocky planets, so they’re made out of rock and material like that. The outer planets are made out of gases.
>
> *Interviewer*: Are these inner planets only made out of rock?
>
> *Laney*: No, they’re probably made out of ice particles, like Mars.
>
> *Interviewer*: What about the gas planets, are they only made out of gas?
>
> *Laney*: Some of them also might have ice too. And a little bit of rock in their core.
>
> *Interviewer*: Are there any ways to group the planets?
>
> *Laney*: These would be the inner planets or rockies. And these would be the outer planets or the gas giants. Similar characteristics.

Laney introduces the idea that some planets have ice as part of their composition. The notion of grouping planets as rocky, gaseous, and icy is relatively new to the field of astronomy. As observations of our own Solar System and others have identified new objects, our scientific models have evolved. More focus has been paid to the role ices play in the formation of planets like Uranus and Neptune, and this is reflected in an increased focus in textbooks and standards on ices as a third important constituent of planetary composition. Therefore, we suggest that the transitions from level to level on this construct map are not particularly challenging for students, but rather, they reflect whether or not students have had opportunities to learn how scientists currently group planets according to defining characteristics.

Construct Map 2: Dynamical Properties of Objects in the Solar System

At the upper anchor of the dynamical properties construct map (Table 2), students describe the Moon orbiting the Earth and the planets orbiting the Sun; they explain that gravity holds the Moon in a constant near-circular orbit about the Earth and its inertia keeps it from crashing into the Earth. A similar explanation is applied to the planets' orbits about the Sun. Students' understanding of how and why objects move in the Solar System was assessed by prompting them to describe how the Moon and planets move and then to explain why those objects move the way that they do.

[Insert Table 2 here.

Table 2. Construct map for the dynamical properties of objects in the Solar System]

This construct map includes the following shifts in understanding: *descriptions* of how objects move and *explanations* for why objects move. At Level 1, students provide non-normative descriptions of the Moon orbiting the Earth and/or the planets orbiting the Sun (Table

2). Students at this level often did not believe that the Moon moves or believed that the Moon follows along with the Earth, without orbiting it, as the Earth orbits the Sun. Starting with Level 2, we have split the construct map into two branches describing different ways of describing *direction* of orbits and the *shape* of the Solar System. This empirically-based split represents two distinct views of the description of planetary orbits that are independent of the explanation of those orbits. Students assigned to levels labelled 'A' understand the planets all orbit in the same direction and exist on a relatively thin plane. Levels labelled 'B' include students who give non-normative descriptions of the planets' orbits, such as moving in different directions about the Solar System or distributed randomly about the Sun, rather than on a plane.

The shift from Level 2 through 5 occurs as students explain orbital motion with increasingly sophisticated uses of gravity and inertia. At Level 2, students use non-normative explanations for why the Moon and the planets orbit. For example, some students discussed the existence of a magnetic-like force holding the Moon in orbit around the Earth. Other students described some type of resistive force keeping the Moon from crashing into the Earth. Across Levels 3 through 5, students use the gravitational attraction between the Earth and Moon and between the planets and Sun to explain why planets remain in their orbits. However, the levels differ in how students explain why the planets do not crash into the Sun or the Moon into the Earth.

At Level 3, students are either unsure why the attractive force between the Earth and Moon or the Sun and planets does not cause these objects to crash or think that the amount of gravitational force is 'just right' to keep objects in a stable orbit. At Level 4, students attempt to use the concept of inertia; however, their explanation indicates that they believe inertia to be a force-like balance to gravity. Lauren (female, 6th grade) articulated this idea in her explanation for the Moon's orbit: 'Because of the Earth's gravitational pulling it in, well not all of the way in because some inertia on the planet is like balancing it together.' She expresses a similar idea, that inertia is a force pulling the planets out, to explain why the planets do not crash into the Sun.

At Level 5, students provide an explanation that includes both a normative view of inertia and gravity, such as the response from Michael (male, 11th grade):

> Sun is the most massive thing in our Solar System, so it pulls all the other planets around it. I guess the planets were in motion, so the reason they go in an ellipse is they're trying to continue their motion, but then gravity pulls them back again. I guess, an object in motion stays in motion. It keeps trying to keep its path, but the gravity continues to pull it back. -- *Michael*

This level of understanding was not typical of the students we interviewed. The major challenge for students in progressing along this construct map is not understanding that a force (i.e. gravity) keeps objects in orbit, but rather in integrating the balance between velocity and gravitational force to explain orbits. This difficulty led us to examine how state and national standards explain orbits. In Pennsylvania, where this study was conducted, the state standards focus on gravity with no indication of the role of the planets' initial velocity or the balance between gravity and inertia (Pennsylvania Department of Education, 2014). Similarly, neither the *Framework* nor the *NGSS* address the role of this balance.

Construct Map 3: Formation of the Solar System

At the upper anchor of the Formation construct map, students apply an understanding of how gravity can be used to explain how a cloud of gas and dust collapsed into a system of planets orbiting a central star (Table 3). Their explanations account for how accretion resulted in a gradual build-up into planets as material 'stuck' together. Students' understanding was assessed through a series of questions about how the Solar System formed followed by questions about a series of representations of the formation.

[Insert Table 3 here:

Table 3. Construct map for the formation of the Solar System]

At the Level 1, students believed that the Solar System has always existed and thus no formation mechanism was needed. At Level 2, students believe that the Solar System began as an explosion and do not include gravity in the formation process. Students at this level often conflate the formation of the Universe, described by the Big Bang theory, with the formation of the Solar System (Prather, Slater, & Offerdahl, 2002). During the interview, students were asked to interpret a sequence of four representations depicting stages in the formation of the Solar System. Despite the fact that the sequence shows a system that gets smaller and smaller, students often still interpreted this as an explosion. This confusion about the Big Bang's role in the Solar System's formation may hinder further progress along the construct map because the Solar System formed during a contraction not an expansion.

There are two forks in the formation construct map, Level 3 and 5, as determined by patterns in students' explanations. Level 3 addresses two groups of students with similar levels of sophistication: students at 3A use an accretion-like process in formation, but not gravity; students at 3B use gravity, but not an accretion-like process. At Level 4, students use both the accretion-like process and gravity in their explanation. The second fork is at Level 5 where again, students show similar levels of sophistication: some use microscopic accretion (5A) and some use macroscopic accretion (5B). At Level 6, students use both micro- and macroscopic accretion to explain the formation of planets. Below, we examine some of the major differences between students' understanding at these different levels, first tracing their use of gravity then tracing their explanations for accretion processes.

Gravity's role in the Solar System's formation. One of the ways that we measured progress was through students' use of gravity. At Levels 1, 2, and 3A, students do not use gravity as part of their explanation for how the Solar System formed. This points to their limited understanding of how gravity works and its role in controlling the movement of objects in space. In particular, we found that students often did not believe that something made of gas would exert a gravitational force, as they believed gas would have little to no mass. Therefore, they had difficulty understanding how gravity could regulate the collapse of a cloud of gas to start the process of Solar System formation.

At Levels 3B, 4, and 5A, students use gravity in the large-scale process of formation or maintenance, such as causing the initial collapse of the cloud or in holding the system together. For example, Timothy (male, 6th grade), at Level 3B, suggested '[Gravity is] pulling it all together… It is like forming it and is what's causing all the energy in the core... [gestures as if gathering material together]. That's the hottest, and that's where the energy is just forming…. Pulling it all together and keeping everything formed like, keeping everything in place. Just keeping everything in alignment.'

At Levels 5B and 6, students use gravity both as a mechanism that causes the collapse of the initial cloud of gas, as well as a mechanism for the accretion process that builds up the planets. Anthony (male, 6th grade), at Level 6, initially described how gravity caused the collapse of cloud of gas and, in the following exchange, explains the planets' formation process:

Anthony: Electromagnetic particle things join together until they gathered enough mass and then the mass would like attract other things and form the planets. And the asteroids are just like left-overs.

Interviewer: Why would the mass pull things together?

Anthony: Er, no the - mass causes gravity and gravity causes [this process].

His explanation clarifies his understanding of how planetesimals accreted material until they had sufficient mass for gravity to pull in additional material to build to a planet-sized object.

Accretion in the formation of the Solar System. At Levels 2, and 3B, students were unsure how the initial materials formed planets. A few suggested that the planets and Sun formed separately and then came together later, without explaining how those planets initially formed. Others offered alternative explanations for how the planets may have formed, including the initial gas cloud becoming solid planets by condensing, or changing states, by cooling off.

Students at Levels 3A and 4 described a process of growth or accretion, distinguished from higher levels by the lack of specificity on the size of the accreting materials and the mechanism causing this accretion. Beth (female, 6th grade) suggests an accretion-like process in her explanation: 'And then there like all like all the dust is kinda, gravity going around the Sun. And there, as the mini planets sorta go around the Sun, they're collecting the debris [to build up].' However, these explanations do not account for how larger objects grew from the initial cloud of gas.

Students at Levels 5A and 6 include an aspect of the formation of planets that includes the process of microscopic materials building up initially by 'sticking' together (they did not need to explicitly use the term *electrostatic force* for this process). Allyson (female, college) provided an attempt to account for building up of smaller particles: 'Once [the cloud is] collapsing, it's gaining rotating and getting hotter. All the dust and particles start forming together. The hot particles fuse together. That's how all the Sun and planets form at the same time.' This explanation reveals some alternative conceptions as she focuses on the materials heating up as a precursor for accretion processes. Savannah (female, 6th grade) explained both the microscopic and macroscopic processes of accretion to build the planets:

> The Sun was formed then rocks and stuff, particles started going around they smooshed up together… then a bunch of hot gases and rocks orbiting around it. Rocks started coming together and still orbited it… More things are coming together. Electrons and all that stuff is building up with each with other… their gravity pull against each other… Once that was big enough they could pull other things together. -- *Savannah*

She uses the term 'electron' rather than a more appropriate term, such as particle, possible confusing this with the concept of an electrostatic force. But the process she describes begins with like-materials sticking together and building up until additional materials could be pulled in via gravity.

Construct Map 4: Gravity

The upper levels of both the formation and dynamical properties construct maps rely on students' use of gravity in constructing explanations. We therefore developed a construct map tracking the progress of students' understanding of gravity in the Solar System (Table 4). The upper anchor describes gravity as a force between two objects with mass. The force of gravity decreases with increasing separation between the objects and there is no limit to this separation.

[Insert Table 4 here:

Table 4. Construct map for the role of gravity in the Solar System]

At the lowest level of the construct map, students have an Earth-centric view of gravity. They believe that gravity keeps things down on Earth and that gravity is a specific trait of Earth.

Gravity cuts off beyond the Earth as well. Tiffany (female, 11th grade) gave some typical response for students at Level 1:

> *Interviewer*: Is there gravity in the Solar System?
>
> *Tiffany*: [No] I don't know what to call it cause when you go out there you're lighter. You float.
>
> *Interviewer*: What have you done about gravity [in class]? Gravity on Earth?
>
> *Tiffany*: Yeah, it pulls you to Earth. Everything you drop, like if I drop that [drops her pen to the ground] it falls. If you drop stuff out there it just kinda floats away.

Tiffany is unsure about whether gravity would cause objects to fall on other planets. She also presents a typical version of the idea that gravity is limited by the extent of the atmosphere and may be caused by some property of the atmosphere.

Among students with different levels of understanding of the role mass plays in determining gravitational force, students also differed in whether they believed the force of gravity extends infinitely or has a boundary. This led us to split Levels 2, 3, and 4 based on students' ideas about the extent of gravity. Students at levels labelled with an 'A' hold some aspects of the normative view that gravity decreases with distance and/or goes on forever. Students at levels labelled with a 'B' believe that gravity cuts off at some distance from an object. For example, many students, like Tiffany, believe that gravity only extends as far as the Earth's atmosphere, though students also indicated cut-offs for gravity at distances from other planets as well.

From Levels 2 through 5, students increase in sophistication in how they explain the cause of gravity between objects in the Solar System. At Level 2, students believe that some objects, but not all, exert a force of gravity. They may believe that the Sun has the strongest gravitational force in the Solar System. They believe that something other than an object's mass causes gravity, such as planets' gravity being caused by the Sun. At Level 3, students understand that an object's mass causes gravity; however, they do not indicate that all objects have mass and thus all objects have gravity. Emily (female, 6th grade) suggests '[p]robably just the inner planets [have gravity] because they have more mass, density.' She does not believe Jupiter, Saturn, Uranus, and Neptune have gravity because 'they're gas and gas is light.' Thus, for some students at this level, their alternative ideas about which objects have gravity often relates to their confusion over whether gas has mass.

At Level 4, students believe that all objects have gravity and that gravity is caused by mass. They are able to identify massive objects as producing the strongest gravitational force or proximity to massive objects as having the strongest gravitational force. Anthony (male, 6th grade) expresses this level of understanding when explaining what causes gravity:

> *Anthony*: Well everything has gravity that has mass. But the Sun just produces the most because it is the biggest, has the most mass.
>
> *Interviewer*: Is there a pattern to the amount of mass and gravity?
>
> *Anthony*: The bigger it is the greater the gravity it has.
>
> *Interviewer*: The bigger the size-wise or mass-wise?
>
> *Anthony*: Mass.

The shift from Level 4 to 5 occurs as students describe gravity as the interaction between two objects with mass. They also understand that gravity decreases with separation between objects and goes on forever. Thus, they identify the strongest gravitational forces as occurring near the most massive objects. Very few students across all grades provided this level of understanding of gravitational interactions.

Discussion

Our findings illustrate how approaching the analysis of student thinking from a LP perspective provides insights into the challenges students have in explaining the current Solar System and its formation, while also drawing attention to areas that instruction can support to help students progress towards understanding of the big idea. While other studies have explored pieces of this learning progression, such as students' ideas about the nature of the Solar System (Sharp & Kuerbis, 2005) or gravity's role in astronomical contexts (Williamson & Willoughby, 2012), our approach is from the perspective of integrating the many dimensions of Solar System astronomy to help students develop explanations of *why* the properties of the Solar System exist the way that they do currently. Uncovering how progress in students' understanding of fundamental principles of physics relates to their progress in explaining phenomena of astronomy adds to the field's understanding of how to support students in making these connections across the science curriculum.

One avenue towards understanding the big idea is learning to explain the patterns in planet compositions by using the model of their formation. We focused on grouping planets by their composition, considering rocky, gaseous, and icy as a normative description of the groups, because instruction on the properties of planets is already a common feature of astronomy curricula. We do not consider learning to group the planets according to their composition to be a challenge for students; instead, our findings suggest students need more opportunities to learn about the planets as a system where planets can be grouped by similar features. Organizing instruction on the properties of planets around the features explained by the formation model instead of having students learn about planets as isolated objects may help teachers move students towards connecting these patterns to how the Solar System formed (Rubin, Plummer, Palma, Spotts, & Flarend, 2014).

We also developed a construct map around the dynamical properties of Solar System objects as these patterns are also explained by the Solar System's formation. The use of gravity as a force keeping planets in orbit was not a significant challenge for students. Instead, the aspect of orbital motion that was most difficult for students was explaining how the planet's own velocity, tangential to the direction of gravitational force, maintains a stable orbit. This aspect of inertia needs greater attention during instruction for students to develop this explanation, such as using Newton's Cannon as a thought experiment during instruction (Velentzas & Halkia, 2013). We also recommend that instruction about planetary motion develop connections to how they are learning about force and motion in Earth-based contexts; our interviews suggest that students have primarily been learning about orbits in terms of gravity, rather than a richer application of physics that helps them understand the role of momentum. Flarend and Palma (2013) recommend that students have the opportunity to use simulations of planetary orbits[1] to gather data on planets' orbital velocities and distance in order to construct scientific explanations using a claims-evidence-reasoning format (McNeill & Krajcik, 2012). Students can use their data to construct an argument for how a planet's velocity depends on distance and justify this using the scientific model for gravity falling off with distance to help address their non-normative ideas about the extent of gravity's influence.

Our development of the formation construct map indicated that one of the major challenges students had in developing more sophisticated explanations was their use of gravity. In particular, at lower levels on the construct map, students did not use gravity to explain the initial collapse of material from a large cloud of gas and dust. And though many students

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[1] One such simulation is available from the Physics Education Technology group (http://phet.colorado.edu/en/simulation/my-solar-system).

explained accretion-like processes and even microscopic accretion processes, where particles stick together through electrostatic forces, fewer students used gravitational force to explain the large-scale build-up of material into individual planets. These difficulties with using gravity to explain phenomena in space may relate to their difficulty understanding that gas can have mass, and thus exert a gravitational force. Thus, instruction may need to address the role of gravity throughout the formation process for students to understand how a cloud of gas and dust could form a system of orbiting planets.

The construct maps we developed towards the physical and dynamical properties upper anchors are not the only possible patterns in the current Solar System that can be explained by the formation model. Rather, we developed these particular construct maps as a first step towards emphasizing a model of student learning that moves towards a broad goal in astronomy: patterns in our current Solar System can be explained by a model of how it was formed. Other possible patterns that can be explained by the formation model include: the Sun and planets rotate in the same direction as planets' orbit, the composition of meteorites reveal the initial composition of the Solar System, and the distribution of planet compositions, with rocky and metal-rich planets close to the Sun and increasing presence of ice in the outer Solar System. Our current Solar System LP and the connections between the construct maps help us understand how students take initial steps towards this level of evidence-based explanation.

Limitations and Future Research

We proposed this as a hypothetical LP because the levels we have mapped are based on trends we observe in student thinking, organized in levels of increasing sophistication, using our interpretation of what counts as productive ideas towards reaching that scientific explanation. This is often the first step in developing a LP (Rogat et al., 2011). Our LP is hypothetical in that we have not presented evidence that this illustrates pathways students may take as they engage with instruction on this topic, nor have we provided descriptions of the types of instruction that help students move from one level to the next. These are some of the important next steps in LP development we plan to take in future publications. LP development is an iterative process requiring cycles of research to fully understand what progress looks like at small scales, such as across one unit in one grade, and at large scales, such as across multiple units and multiple grades.

We also point out the importance of testing these construct maps during diverse instructional conditions in order to begin examining how students make connections between the constructs; ultimately, it is by making those connections (such as using the formation process to explain the patterns in planet compositions) that allows us to understand how students move towards the LP's big idea. Our use of evidence to develop the construct maps was limited by having few students at the upper anchors; it is at these upper levels of the construct maps that students have the necessary understanding of the context and scientific principles to begin making connections between the current Solar System and its formation. Future research that examines students who have participated in instruction around this big idea, using the construct maps as rubrics to measure progress, will help us identify ways that instruction supports students in making connections across the big idea.

Acknowledgements

[Removed for review.]

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Table 1. Construct map for physical properties of objects in the Solar System

Level	Description
5	The Solar System contains planets, the Sun, and possibly asteroids, moons, and comets. The planets are composed of all or mostly rocky, gaseous, and/or icy materials and can be grouped based on their primary material. The Sun is composed of gas or plasma.
4	Planets are described as all or mostly rock, gas, or ice (though *usually* as primarily rocky or gaseous at this level). Planets can be grouped based on their composition. [a]
3	Planets are described as all or mostly rock, gas, or ice (though *usually* as primarily rocky or gaseous at this level). Planets' compositions are not used as a grouping criterion. [a]
2	At least one planet's composition is normatively described as rocky or gaseous. Additional normative compositions are not known, nor are planets grouped according to normative descriptions of their compositions. [a]
1	The Solar System includes normative objects, such as some planets and the Sun, but also non-normative objects, such as stars and black holes. Planetary composition and grouping are non-normative.

[a] At these levels, the Solar System includes normative objects, such as planets and the Sun, but may also include non-normative objects, such as stars and black holes. The Sun's composition may or may not be accurately known.

Table 2. Construct map for the dynamical properties of objects in the Solar System

Level	Description	
5	Orbits in the Solar System are the result of a balance between the object's tangential velocity and the gravitational force between the object and the body it is orbiting.	A: The Solar System is relatively flat and the planets orbit in the same direction.
		B: Descriptions of the shape of the Solar System and/or the direction of planetary orbits are non-normative.
4	Orbits in the Solar System are the result of a balance between two forces: the	A: The Solar System is relatively flat and the planets orbit in the same direction.

	gravitational force (between the object and the body it is orbiting) and some other inaccurate force; the role of an object's tangential velocity in maintaining a stable orbit is not accurately explained.	B: Descriptions of the shape of the Solar System and/or the direction of planetary orbits are non-normative.
3	Orbits in the Solar System are the result of the gravitational force between objects, holding one in orbit about another. Unclear or non-normative reasoning for why objects do not crash into the object they orbit.	A: The Solar System is relatively flat and the planets orbit in the same direction.
		B: Descriptions of the shape of the Solar System and/or the direction of planetary orbits are non-normative.
2	The planets orbit the Sun and the Moon orbits the Earth, but the student provides non-normative reasoning for why objects maintain their orbits.	A: The Solar System is relatively flat and the planets orbit in the same direction.
		B: Description of the shape of the Solar System and/or the direction of planetary orbits are non-normative.
1	The Moon does not orbit the Earth and/or the planets do not move or do not move along distinct orbits about the Sun.	

Table 3. Construct map for the formation of the Solar System

Level	Description	
6	The Sun and planets formed from the same initial cloud of gas and dust. Gravity caused the collapse of this material into the Sun and planets. After the initial collapse of the cloud, objects in the Solar System formed from the accretion of microscopic materials such as gas, rock, and/or dust that built up until the collection was massive enough for gravity to continue the accretion process at the macroscopic level. [a]	
5	The Sun and planets formed from the same initial cloud of gas and dust. [a, b]	
	A: Gravity caused the initial collapse of this material but not the formation of the individual planets. After the initial collapse of the cloud, planets formed by the accretion of microscopic materials such as gas, rock, and/or dust.	B: Gravity caused the collapse of this material. The Solar System formed from macroscopic materials such as gas, dust, or rocks. Planets were formed by the accretion of this macroscopic material using gravity as part of this process.

4	The planets formed from materials such as gas, rock, and/or dust. Formation includes accretion-like processes; however, this mechanism is not microscopic material sticking together or governed by gravity at a macroscopic level. Gravity plays a role in the formation or maintenance of the whole system. [a, b]	
3	A: The planets formed from some pre-existing materials in some type of accretion-like process; mechanism not clearly microscopic material sticking together or governed by gravity at a macroscopic level. Gravity plays no role in formation or maintenance of the system. [b]	B: No mechanism for how planets formed from pre-existing materials. Gravity plays a role in the formation or maintenance of the whole system, but not in forming the planets. [a, b]
2	The Solar System began as an explosion. No mechanism provided for how planets formed from pre-existing materials. Gravity plays no role in formation or maintenance of the system.	
1	The Solar System has always existed.	

[a] Description of the force of gravity may include non-normative aspects.
[b] Formation may have occurred after an explosion.

Table 4. Construct map for the role of gravity in the Solar System

Level	Description	
5	Gravity is a force caused by an interaction between two masses. Gravity decreases with separation between the objects and goes on forever. Massive objects produce the strongest gravity or proximity to a massive object produces the strongest gravity.	
4	All objects have gravity, which is caused by mass. Massive objects produce the strongest gravity, the Sun has the strongest gravity, and/or proximity to a massive object produces the strongest gravity.	A: Gravity decreases with distance and/or goes on forever.
		B: Gravity cuts off some distance from the objects in question.
3	Specific objects have gravity (e.g., Sun, Earth, Moon, but not Jupiter), which is caused by mass. Massive objects produce the strongest gravity and/or the Sun has the strongest gravity.	A: Gravity decreases with distance and/or goes on forever.
		B: Gravity cuts off some distance from the objects in question.
2	Some, but not all, objects have gravity (e.g., Sun, Earth, Moon, but not Jupiter), and the Sun as has the strongest gravity. Non-normative explanations for the cause of gravity.	A: Gravity decreases with distance and/or goes on forever.
		B: Gravity cuts off some distance from the objects in question.
1	Gravity keeps things down on the Earth and is a specific trait of Earth (i.e. Earth is special). The Earth's gravity has a set limit where it cuts off. Gravity is strongest on Earth.	