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LEARNING

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Evaluating a learning progression for the solar system: Progress along gravity and dynamical properties dimensions

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Abstract

We previously proposed a hypothetical learning progression around the disciplinary core idea of the Solar System and its formation as a first step in a research program to begin to fill this gap and address questions of student learning in this domain. In this study, we evaluate the effectiveness of two dimensions within the learning progression, dynamical properties and gravity, in describing change in how student reason in the domain across the course of their 14-week astronomy unit. A sample of sixth-grade students ($N = 24$) were interviewed before and after instruction. We compared changes in how students explained the dynamic properties of planets and the role of gravity in the Solar System to their experiences during instruction. Our findings provide evidence for the usefulness of this learning progression in describing how students' explanations may progress, offer insight into how instruction may support that progress, and highlight the challenges in drawing conclusions on how students' explanations may progress when limitations are identified in instructional experiences. We also discuss the connection between these two construct maps but also point out what appears to be a missing element in our original definition of the learning progression: inertia.

KEYWORDS
astronomy, learning progression, middle school

1 | INTRODUCTION

The Next Generation Science Standards (NGSS) propose an ambitious goal of supporting students' development of increasingly sophisticated explanations for big ideas in science. For many of the core ideas included in the NGSS, we have only a limited understanding of how students' understanding may progress over time and the nature of instruction that supports their learning. Instead, the preliminary *learning progressions* proposed in the Framework for K-12 Science Education (*Framework*; NRC, 2012), from which the NGSS were developed, are based on analysis of the disciplines and relevant studies of students' ideas. While this is an important first step in understanding how to develop appropriate standards and instruction, more empirical research is needed that considers how students' understanding of disciplinary core ideas changes over time through appropriate instruction (NRC, 2012). Research on instruction that supports student learning and identifies areas that remain challenging for students is necessary to develop curricula to support students and teachers in achieving the goals of the NGSS.

One area emphasized in the *Framework* is the Earth's Place in the Universe (NRC, 2012). From this core idea, we draw the following: the patterns of movement and composition of objects in the current Solar System can be explained using fundamental laws of physics and a model of the Solar System's formation. Though previous research has considered elements of student thinking (e.g., Sharp, 1996) or learning (e.g., Sharp & Kuerbis, 2006) about components of this core idea, more research is needed to understand how to best support students as they develop coherent explanations for astronomical phenomena explained by the Solar System formation model. While prior research helps us understand some challenges students have in accurately applying gravity to explain Solar System phenomena, orbital motion in particular (Treagust & Smith, 1989; Velentzas & Halkia, 2013; Yu, Sahami, & Denn, 2010), these studies often are limited to students' conceptions, rather than the role of instruction; or, they only consider student learning at high school and college level. Another critical component this study considers are students' ideas about the role of tangential velocity in explaining orbits and how instruction might support students at the middle school level, where they begin to construct these explanations.

We previously defined a hypothetical learning progression (HLP) describing increasing levels of sophistication in describing and explaining the Solar System and its formation (Plummer et al., 2015). In this study, we take next steps toward validating our HLP in an instructional context as we examine two dimensions of the HLP, how and why objects orbit in the Solar System and the nature of gravity in the Solar System. Our work considers how 6th grade students' ideas developed in sophistication after participating in an astronomy unit designed around the big idea of our HLP. We analyzed the relationship between students' experiences in the classroom and how their ideas changed as described by the dimensions of our HLP. The following research question was used to guide our study: How can patterns in student thinking before and after instruction about dynamical properties and gravity, as measured by the hypothetical Solar System LP: (a) provide evidence for the validity of the LP, (b) reveal elements of instruction that support students' progress along the LP, and (c) identify connections between the dimensions within the LP?

2 | DEVELOPING AND VALIDATING LEARNING PROGRESSIONS

Learning progressions (LPs) are empirically derived descriptions of how learners' conceptualizations of big ideas in science increase in sophistication through the mediation of instruction (e.g., Corcoran, Mosher, & Rogat, 2009; Duschl, Schweingruber, & Shouse, 2007; Krajcik, Sutherland, Drago, & Merritt, 2012). LPs go beyond focused studies of how students learn key concepts or practices in science by taking a broader and often, a longitudinal view, of how students learn big ideas that have broad explanatory power over multiple phenomena and contexts.

Our LP is based on three core tenets of LP design, as drawn from the literature. First, LPs are designed around a big idea in science that serves as the upper anchor for the LP and helps students make sense of a multitude of phenomena (Krajcik et al., 2012; Smith, Wiser, Anderson, & Krajcik, 2006). Second, LPs include descriptions of intermediate levels of sophistication, which are often referred to as “stepping stones” because of how they allow students to bridge from one level to the next, with appropriate instruction (Duschl, Maeng, & Sezen, 2011; Smith et al., 2006). At the lower anchor of the LP are initial, naive conceptions, often based on students' own observations and experiences with the world. Third, because LP levels are not developmentally inevitable (e.g., Krajcik et al., 2012; Metz, 2009), several researchers recommend that LPs include instructional elements that can support students as they move from one level to the next (e.g., Krajcik et al., 2012; Rogat et al., 2011; Smith et al., 2006).

Big ideas often contain sufficient complexity that they include multiple possible dimensions across which students may potentially improve. In our development of the Solar System LP, we examined how students' thinking shifted along the dimensions of physical properties, dynamical properties, the formation model, and gravity. As a result, we drew on Wilson's (2009) *construct maps* as an organizational structure. Each construct map is similar to an LP in how it describes increasing levels of sophistication. But rather than having a big idea as the upper anchor, the top level of each construct map is one dimension of the Solar System big idea.

The use of construct maps in the LP model allows us consider possible connections between the dimensions as students progress toward understanding the big idea. Developing multidimensional LPs begins with generating evidence that identifies contingencies: the relationships between construct maps (Plummer & Maynard, 2014; Shea & Duncan, 2013). One goal of LP research can be to look for trends in how students progress across multiple construct maps to identify possible relationships between levels in those different construct maps. This can help teachers and curriculum developers plan for how instruction should be sequenced to support learning across the curricula.

LP development often begins by reviewing available literature on students' ideas and unpacking the big idea to identify potential dimensions (Rogat et al., 2011). If sufficient literature on student thinking exists, this can be used to map out a hypothetical LP (e.g., Smith et al., 2006). To develop our original Solar System LP, we complemented this approach with additional data from cross-age samples to aid the development of the HLP through student interviews (Plummer et al., 2015). This offered a set of potential levels of sophistication for students' ideas, but did not suggest how students' ideas might change as a result of instruction tied to the big idea nor were we able to identify areas that may be challenging for students even with instruction. According to Alonzo (2018), LPs “are frameworks for reasoning about students' ideas. By laying out the landscape that students traverse coming to full understanding of a topic, learning progressions both focus attention on specific aspects of students' ideas and provide a structure for interpreting and responding to those ideas” (p. 107). Thus, an important feature of empirical validation of an LP is to investigate the extent to which an HLP may be useful in describing students' explanations in the context of instruction designed to support development of the big idea across time (Krajcik et al., 2012; Lehrer & Schauble, 2015; Metz, 2009). The HLP can then be treated as a hypothesis by comparing the patterns in students' thinking across instruction to the description of the HLP, generating potential evidence for the validity of the HLP in the context of that instruction as well as informing the utility of the model in describing trends in how students' ideas change over time.

One challenge LP researchers face is the variance observed in student thinking as measured across contexts or by items within an assessment. For example, Alonzo and Steedle (2009) found that students often responded inconsistently to similar questions set in different contexts when reasoning about force and motion. Gotwals and Songer's (2010) investigation of students' reasoning about food chains revealed variations in how students reason depending on contextual information in the assessment. Hokayem and Gotwals (2016) also found that students were reasoning at different levels on their LP within individual open-ended questions they used to assess students' thinking about ecosystems. Thus, assigning an individual student to a specific LP level may provide challenges to be monitored in the validation process. Indicating where student thinking maps onto the LP is not meant to represent stability in student thinking given that students are likely to express different ideas when assessed in different contexts. Rather, LP development and validation can be considered to be a process of looking for patterns across multiple students' ideas to determine whether a model of cognition (the LP) is productive at describing possible stepping stones. That is, which levels may represent more potential for stability as they offer students useful ways to explain the big idea within the contexts used for measurement (Sevian & Talanquer, 2014). We took this approach of comparing student thinking by conducting interviews before and after instruction to our LP levels in an effort to examine whether our earlier hypothetical LP provide useful descriptions of potential stepping stones.

3 | THE HLP FOR THE SOLAR SYSTEM

While other LPs describe each level in terms of profound changes in how students view the world (e.g., shifting from force-dynamic reasoning to scientific model-based reasoning; Gunckel, Covitt, Salinas, & Anderson, 2012), our construct map levels describe progress in ways that include both elements that are similar from one level to the next and elements that demonstrate how students' explanation for the big idea are qualitatively different. Following on Rogat et al.'s (2011) recommendation to identify "coherent views that act as useful scaffolds to focus students' attention on aspects of the phenomenon upon which they can build their thinking as they move to the next level, closer to the canonical contemporary view" (p. 7), we described in our previous paper how shifts in student ideas from one level to the next may form productive steps (Plummer et al., 2015). In our construct maps, each shift from one level to the next results in improved sophistication in at least one element of the student's explanation, while other elements may remain less sophisticated and even continue to include nonnormative explanations for the phenomena. Our approach to defining the construct maps in this way was determined by the nature of the discipline, in that progress in understanding and explaining dynamics in the Solar System results through the application of systems thinking as students apply knowledge of the physical system (properties and dimensions) as well as understanding of two laws of physics (gravity and inertia). It was also shaped by the grain-size of ideas which we believe will be useful for teachers, assessment writers, and curriculum writers to use in the future (Hokayem & Gotwals, 2016; Plummer & Maynard, 2014).

As the focus of this paper is on validation of the dynamical properties and gravity construct maps, we will focus on those aspects here. The dynamical properties construct map was developed around the upper anchor (see Supporting Information—Appendix A—for the full construct maps):

> *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. The Solar System is relatively flat and the planets orbit the Sun in the same direction.*

At the upper levels, explanations include tangential velocity as a reason for why planets do not crash into the Sun. We also found that a more sophisticated explanation for orbital motion did not always include a description of the planets' orbits around the Sun as being in the same direction and on relatively the same plane. In other words, in some cases the physics of orbits was productively characterized without articulating the descriptive context of our Solar System, while in others the context was productively explained without characterizing an understanding the physics. For this reason, we developed subdesignations A and B for each of the upper four levels to account for these differences.

Given the importance of gravity to explaining both orbital motion and the Solar System's formation model, we considered this construct in a separate construct map. The gravity construct map was developed around the following upper anchor:

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.

More research has been conducted on students' ideas about gravity, in general, than orbital motion, though much of this has focused on Earth-based applications (Kavanagh & Sneider, 2007; Treagust & Smith, 1989). We found the notion that gravity decreases with distance yet goes on forever did not correlate with other notions of gravity. Therefore, we defined increases in sophistication based on whether the explanation used mass to define gravity and then we added two subdesignations: A for the normative idea that gravity goes on forever; and B for the nonnormative idea that gravity cuts off at some distance.

4 | METHODS

We used the *assessment triangle* (National Research Council, 2001) to guide an iterative process analyzing students' ideas, change in those ideas across the levels of the LP, and the role instruction played in that change. The *assessment triangle* represents the key elements of assessment at its vertices: a model of student *cognition* or learning; a purposeful selection of *observations* which provide evidence of students' ideas; and a method of *interpretation* to make sense of the evidence gathered. The model of cognition was our HLP, as this describes our hypothesis of how students' ideas about the Solar System may change across instruction. Unlike many other studies that have examined written assessment data to provide evidence for a LP, our observations were based on pre- and post-instruction, clinical interviews with students (Ginsburg, 1997). This method has been previously used to provide evidence for LP validity in a few studies (e.g., Hokayem & Gotwals, 2016; Plummer, 2014; Wyner & Doherty, 2017). Our method of interpretation consisted of aligning coded interviews with the levels of each construct map. This method has the advantage of providing opportunities to probe and clarify student responses during interviews while also allowing us to see the same students both before and after instruction to look for patterns of change in understanding, as measured by the LP.

We add to our use of the assessment triangle, as a development cycle, the analysis of classroom instructional video; this allowed us to assess the relationship between students, experiences during instruction and how their ideas changed levels along the construct maps from before to after. Our study context takes place in one 6th grade teacher's classroom. Therefore, the findings are not representative of all possible LPs for this domain. Rather, we point to the importance of conducting studies that focus on a small grain-size, such as across a single unit with a single grade level (e.g., Plummer & Maynard, 2014; Yin, Tomita, & Shavelson, 2014). By examining how a small group of students' ideas changed and how this change was supported by their experiences with one specific curriculum, we can focus on those elements of instruction which may become useful tools for future curriculum development or allow for future scaling up when evaluating this LP (Gotwals, 2012; Plummer & Maynard, 2014).

4.1 | Setting

Participants were students drawn from five classes of 6th grade students, all with the same science teacher, Mrs. A.[1] The students attended a public middle school in a small town in central Pennsylvania. The majority of students (95%) are European Americans (Public Schools K-12, n.d.). Twenty-seven percent of students are eligible for free or reduced lunch.

During the summer before this study, Mrs. A attended a week-long summer professional development (PD) led by the study's coauthors. The PD was designed to help teachers learn how to adapt their astronomy curricula into a *coherent science content storyline* (CSCS) by engaging the teachers in a series of middle school appropriate investigations leading toward the big idea of the Solar System's formation. CSCS emphasizes the importance of designing the sequencing and connecting lessons within a curriculum in ways that make key science ideas explicit and move students toward understanding a single big idea in science (Roth et al., 2011). The PD also emphasized the use of scientific argumentation using a claims-evidence-reasoning framework throughout the investigations (McNeill, Lizotte, Krajcik, & Marx, 2006).

Mrs. A designed her 14-week unit on astronomy toward the big idea of the Solar System LP but was otherwise not guided by the LP itself; she was not familiar with the details of the LP, its construct maps, or the levels. Mrs. A adapted investigations from the summer PD, added other lessons which helped her address state science standards, and sequenced them toward the big idea of how the Solar System formation model explains current patterns in the Solar System (see Supporting Information Materials for Table S1—Overview of Mrs. A's curriculum). Of this, approximately 9 weeks directly addressed content within the Solar System LP, and seven of those weeks contained a lesson or lesson-set on content relevant to the two construct maps we investigate in the present study. Mrs. A engaged students through small group and whole-class discourse as they developed evidence-based explanations for the shape of the Solar System and planetary orbits, among other investigations. Classroom investigations were often supported by students' use of computer simulations (Starry Night and the PhET simulation, My Solar System[2]) as well as the use of physical and kinesthetic modeling activities.

We can trace how the dynamical properties and gravity concepts were developed through the curriculum. Mrs. A's CSCS began with explaining observable phenomena using the orbital motions of the Earth and Moon in the Solar System. Students applied concepts of gravity and inertia to explain the phenomena of tides. Students continued to construct explanations for observed phenomena, including using the pattern of the planet's appearance in the constellations to determine that the Solar System is relatively flat with planets orbiting in the same direction. These investigations led to whole-class conversations about the role of gravity and inertia in explaining Solar System orbits. Planetary orbits were then investigated using a simulation that allowed students to explore the factors that control gravity and inertia. Investigations of planetary properties introduced further questions of how a planet's density relates to the gravitational force it produces. Students also explored the role of gravity in the Solar System and the nature of planetary orbits as they simulated the Solar System's formation model.

4.2 | Data collection

Students were interviewed before and after instruction using the same open-ended interview protocol. Twelve male and 12 female students were randomly selected from those who returned signed consent forms to be interviewed ($N = 24$). The interview protocol, refined through rounds of pilot testing and a previous study (Plummer et al., 2015[3]), engaged students through questions about the motion of objects in the Solar System, why planets orbit the Sun, and their knowledge of the nature and extent of gravity in the Solar System (along with other topics beyond the scope of this manuscript). Interviews, lasting 20–35 min, were video and audio recorded for analysis (see Supporting Information Materials for Supporting Information Appendix B: Interview Protocol). Across the astronomy unit, 31 days of instruction were video and audio recorded. Other lessons were not recorded because either the topic was outside the scope of this LP or students were not in school (e.g., snow days, state testing, field trips).

4.3 | Data analysis

4.3.1 | Construct map validation

Our analysis looked across each student's full interview to assign codes that correspond to their ideas about specific concepts within the four categories that made up each construct map. Student ideas, both normative and nonnormative, were represented in the codes and categories presented in Supporting Information Materials as Supporting Information Appendix C. Inter-rater reliability was established by having two authors independently code a random selection of 10 interviews. This process was repeated until at least 80% agreement was reach for each category; any disagreements were discussed and resolved to improve the team's interpretation of the coding protocol. An inter-rater reliability analysis using the Kappa statistic was performed to determine consistency among raters. The results of our inter-rater analysis were Kappa statistics between 0.697 and 1.00 ($p < .001$). This agreement is statistically significant and, according to Landis and Koch (1977), is considered almost perfect agreement for most categories and substantial agreement for two categories.

Next, we aligned each students' interview response to a construct map level using their specific combination of codes, both normative and nonnormative ideas, within each of the four categories that make up a construct map. Table 1 shows an excerpt from the Dynamical Properties construct map as an illustration of this process while the full construct maps, categories, and codes, are available in Supporting Information Appendix D. Construct map levels were defined by grouping codes in ways that showed student thinking increasing in sophistication toward the upper anchor. The codes shown for level 3B (Table 1) are those that are used to define that construct map level; they define the characteristics of what type of explanations were categorized to that level. The existence of multiple codes is because we (a) we split the full explanation we were looking for in to separate ideas to code for (e.g., we coded for why planets stay bound in orbit separately from why they do not crash into the Sun), (b) we coded for different ways students expressed similar ideas allowing for both variation in students' explanations at a given level but also nuance in our coding scheme, and (c) we grouped some amount of variation into lower levels (e.g., Level 3) when there was consistency in one aspect of their reasoning. For example, code B, E, or M for the Planets Orbit category indicates that students believe that gravity keeps planets in orbit (the E code indicates students referenced their explanation for the Moon's orbit which used gravity; M code adds the caveat that students also think there is *just the right* amount of gravity to keep planets from crashing into the Sun). The other codes at this level describe how students explained why planets do not crash into the Sun: they either provided other specific nonnormative reasons (G, I) or were unsure (K, U). These differences across their reasoning for why the planets do not crash into the Sun did not form a sufficient pattern from which to split this into further levels. Thus, we defined this level around the use of gravity to explain orbits. On the few occasions where a students' ides were assigned codes that crossed levels (e.g., when students gave different explanations for the Moon's orbit and the planets' orbits), the students' explanation was assigned the less sophisticated level as achievement of the higher level required application of the more sophisticated levels of reasoning across all categories defining that level. However, we are limited in this analysis as we were only able to assess each student's ideas in one context (one explanation of their understanding of the Solar System and its motions) and only at two-time points. A given student may hold other ideas that could be expressed and measured to be at a different level on the Construct Map and that this may change depending on the conditions in which we measure those ideas.

We then plotted the change for each students' pre-to-post response based on the construct map levels using a slopegraph. Slopegraphs are graphical representations depicting "changes over time for a list of nouns located on an ordinal or interval scale" (Tufte, 2014, Slopegraphs for comparing gradients, para. 1). Analyzing the trends in how student idea levels on the construct maps changed pointed us to conceptual areas to investigate further through analysis of the instruction. For example, one trend observed was that the majority of students gave gravity explanations consistent with Level 2B before instruction and explanations consistent with Level 4B after instruction. This shift in how students characterized gravity in the Solar System pointed us toward analyzing the opportunities afforded by the instruction to learn about gravity in ways that may have supported that specific pattern of change.

TABLE 1 Excerpt from the dynamical properties construct map showing the alignment of categories and codes to levels

Level	Level descriptions[a]	Planets/Moon move codes	Moon orbit codes	Planets orbit codes	Shape codes
3B	Orbits in the Solar System are the result of the gravitational force between objects, holding one in orbit about another. Believes the amount of gravitational force is "just right" to keep objects in a stable orbit, provides another nonnormative reason, or is unsure why objects do not crash into Sun/Earth. Ideas about the shape of the Solar System **and/or** for the direction of planetary orbits are nonnormative.	G; D or L (other codes can be accurate)	B, D, and/or L; also possibly E, F, G, H, I	B, E, and/or M; also possibly G, I, K, U	B, C, D, E and/or U (other codes can be accurate)

[a]This column is based on the original description published in Plummer et al. (2015).

4.3.2 | Analysis of instruction

The instructional analysis focused primarily at the whole-class level rather than looking at how individual students engaged in the instruction or how small group conversations supported their cognition in this domain. We made this decision as our goal was to suggest links between broad trends in the opportunities afforded by the curriculum and improvement, as measured by changes in levels on the LP.

To improve the reliability and accuracy of our analysis of the instruction, we went through three iterations of coding (using the software *StudioCode*). This iterative process increased the likelihood that we had identified all relevant aspects of instruction, as multiple coders viewed the video corpus in each round of coding. Iteration 1: We coded instructional videos using the same categories developed for the student interviews, allowing us identify the conceptually relevant segments of instruction using the same system of codes and categories as used in the interviews. Doing so increased the construct validity of our analytical system.

Iteration 2: Next, we applied the *upper anchor codes*: codes that make up the concepts in the upper anchors of the construct maps (however, after finding that instruction was limited on the component of the gravity upper anchor, "gravity is the interaction of two masses," we added a code that addressed the similar idea from the level below "gravity is caused by an object's mass"). Because each upper anchor is made up of multiple codes, some include codes that also help us identify student thinking at levels below the upper anchor. For example, the idea that gravity between objects keeps objects in orbit occurs in the Upper Anchor, but also in Levels 3 and 4 so this component code (gravity keeps objects in orbit), as drawn from the Upper Anchor, could also be used to identify appropriate instruction that helped students who were at lower levels (e.g., Level 1 and 2) learn part of the Level 3 explanation. Thus, this helped us identify instruction where the teacher was working with different aspects of what it meant to help students' ideas improve toward the big idea. These sections often included dialog between teacher and student where the teacher provided support for students along one or more elements of the upper anchor.

Iteration 3: We applied four *instructional codes* to describe how teachers and students were interacting in the classroom around key concepts: (a) *Sense-Making Multi-Student Teacher* (SMMST) involved teacher and students in sense-making conversations: all or nearly all students are involved or have the opportunity to be involved; (b) *Sense-Making Limited Student Involvement* (SMLSI) involves intellectual depth around the concepts, but involves only the teacher and a few students; (c) *Simple Question Answer* (SQA) is characterized by the teacher asking simple factual response questions or providing a more passive observational experience, such as participation in a round of initiate-response-evaluate, common to classroom discourse (Lemke, 1990) or a demonstration that the students primarily observe rather than an engaging discussion; (d) *Collecting Data* was used when students were collecting conceptually relevant data. All instruction, as identified in iteration 2, fell into one of these four codes.

In the final phase of analyzing the instructional video, we were guided by trends in the construct maps' slopegraphs as we returned to those instances of instruction previously identified as conceptually supporting improvement as defined by the construct maps. Specifically, the *upper anchor codes* provided an initial starting point to focus on instructional opportunities related to specific slopegraph trends. This allowed us to look at the instruction that may have supported student learning of key elements between each level, such as from Level 2 to 3 and from 3 to 4 when the overall trend was from Level 2 to 4. *Instructional codes* were then used as we considered how the class was involved in relevant sense-making within the domain of that construct map. Two members of the research team collaboratively wrote analytic memos of the relevant instructional segments matched to specific trends and transcribed key portions of whole-class conversation. This process also involved returning to our use of the full set of interview codes for dynamics and gravity, as applied to the instructional videos, to consider the full range of ways instruction may or may not have supported productive change in students' ideas. These additional elements of instruction were then added to the rich descriptions of instruction in the analytic memos and grouped by slopegraph trend.

The team reviewed and discussed the analytic memos describing the relationship between instruction and slopegraph trends along the LP to form conjectures. These conjectures focused on opportunities for sense-making in the classroom around critical constructs, gaps between instructional supports and the upper anchor of the LP, potential opportunities for misunderstanding of scientific ideas during instruction, and the duration, depth, and/or iterative nature of opportunities for learning in the context of instruction. Across our analyses, we considered where change in students' ideas was inhibited due to the challenging nature of the concepts and but also where opportunities for students to learn were missing. Similarly, we considered whether some trends toward learning might be due to the relative simplicity of the concepts (as compared to those requiring more sophisticated reasoning) rather than specific factors of the instruction.

5 | FINDINGS

Our findings are organized around the two construct maps on which we focused our analysis: *dynamical properties of objects in the Solar System* and the *role of gravity in the Solar System*. In each section, we begin by discussing shifts observed in students' explanations as measured by the construct map levels and represented as slopegraph trends. We then discuss those findings identified by comparing students' experiences during instruction to specific trends observed in changes in students' ideas as measured by the Solar System LP. As LPs are a combination of descriptions of sophistication in how students explain big ideas in science and the instruction that supports improvement, we analyzed students' experiences during instruction and describe here our potential instruction-based conjectures for patterns in student explanations.

5.1 | The dynamical properties construct map

The slopegraph in Figure 1 provides a visualization of how students' ideas changed, along the dynamical properties construct map. Each line shows the trajectory of one or more students' idea from pre- to post-instruction. The thickness of the lines are proportional to the number of students who followed that same trajectory. The overall trend was one of moving from lower to higher levels. Further, we found that nearly all students' responses could be assigned to a single level on the construct maps. Only two students for each construct map (one pre- and one

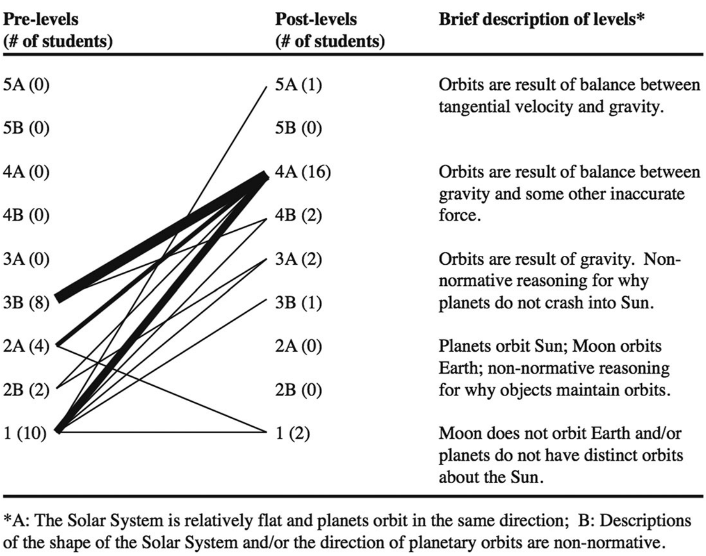

FIGURE 1 Change in students' ideas along the dynamical properties construct map. The number of students whose ideas were measured at each level, before and after instruction, is indicated parenthetically. The thickness of the line corresponds to the number of students whose ideas indicated that transition. Full descriptions of each level appear in Supporting Information Appendix A [Color figure can be viewed at wileyonlinelibrary.com]

post-interview for dynamic properties; two postinterviews for gravity) gave responses that were coded in ways not entirely consistent with our levels (for one category defining the level they gave a more sophisticated response than the rest of their answers).

Before instruction, the students' ideas were at levels 3B and below (the "B" modifier indicates a nonnormative description of the shape of the Solar System and/or shared directionality of planetary orbits). Most students' ideas were either in Level 1 (nonnormative beliefs about how the Moon orbits the Earth and/or how the planets orbit the Sun) or Level 3 (using gravitational force to explain why objects do not escape their orbits, but suggesting objects do not crash into the object they are orbiting because they have the right amount of gravity or some other alternative idea; Figure 1).

The major trend observed was an improvement in ideas expressed from explanations at Levels 1, 2A, and 3B, before instruction, into level 4A, after instruction. This broad trend can be broken into four areas of improvement or partial improvement: (a) The change from students expressing ideas at Level 1 into Level 4 showed evidence of learning that the Moon orbits the Earth, and the planets orbit the Sun. (b) The change from Level 1 and 2 into Level 4 shows improvement in how students explained planets' orbits by including the force of gravity as the mechanism preventing objects from escaping their orbits. (c) Expressing a Level 4 explanation indicates that student suggested there was something preventing planets from crashing into the Sun, or the Moon into the Earth, which they often referred to as inertia. However, at this level, the explanation of what balances the force of gravity pulling a planet toward the Sun was more akin to a force rather a normative description of inertia. (d) Most of these students' ideas trended toward the improved idea that planets orbit the Sun in the same direction and on a relatively flat plane (shift from a B level to an A level). These four trends are discussed below.

5.1.1 | Improvement trend: Orbital motion (out of Level 1)

The *orbital motion* trend described students' ideas shifting out from Level 1 as they learned the Moon orbits the Earth, and the planets orbit the Sun; the description of planets orbiting the Sun and the Moon orbiting the Earth appears at all levels higher than Level 1. Our analysis suggests that students had multiple opportunities to apply ideas about orbital motion during lessons across multiple weeks of instruction and that opportunities to learn this concept were supported through teacher-led discussions around physical and computer-based models. For example, during a lesson on tides, Mrs. A used both physical and computer-based models in ways that required students to use the Moon's orbit to explain the tides phenomenon (Week 5). Physical models, such as using a basketball to represent the Moon and a globe to represent the Earth, were used during an interactive discussion of how the Sun-Earth-Moon system can be used to relate the phases of the Moon to the spring and neap tide (Week 5). Students then observed and discussed a dynamic computer visualization of the relationship between the Moon's orbital motion and the location of tides. Students also used a computer simulation of orbital motion in Week 11 when investigating the factors that produce stable orbits.

Students applied knowledge of planetary orbits to investigate how observations of planets' locations with respect to the constellations can be used to determine the shape of the Solar System (Week 8). Rather than explicitly teaching the concept of planetary orbits, our analysis suggests Mrs. A assumed students understood that planets orbit the Sun, based on the questions and assumptions made in her comments during the discussion in this and other investigations. During the investigation, students collected data using a computer simulation of the planets' appearance in the sky (*Starry Night*). As a class, students analyzed their observations and constructed an explanation describing the flat-nature of the Solar System, discussed further below. Mrs. A asked the students: "From our vantage point from Earth, if we look out at the backdrop of stars and this backdrop is the one that all the planets pass in front of, what does it tell us about how the planets travel?" Answering this question relies on understanding how planets move in relatively circular orbits in the Solar System. In response to this investigation, we observed students gesturing in a circular motion in small group conversations as they discussed how the planets orbit in the Solar System.

In summary, our analysis suggests the *orbital motion* improvement trend was supported by multiple opportunities across the curriculum to observe and discuss how orbits can be used to explain phenomena, supported with both physical and computer-based models.

5.1.2 | Improvement trend: Using gravity to explain orbits (out of Levels 1 and 2)

The *using gravity to explain orbits* trend describes how, at levels above Level 2, students' ideas incorporated the force of gravity as the mechanism preventing objects from escaping their orbits in their explanations. Our analysis suggests that discussions which arose from questions posed by students or the teacher provided students with the opportunity to make sense of the concept of gravity's relationship with orbits, across the curriculum. Further, students' opportunity to apply gravity to explain why planets orbit the Sun during an investigation of planetary orbits may have further contributed to how their ideas shifted up to this level on the construct map.

An example of this, a discussion applying gravity to orbits, began as Brianna asked why the Moon orbits the Earth and is not pulled into the Sun, given that the Sun has more mass; this led to further discussion of gravity and its role in orbits (Week 9). In a later lesson, Mrs. A posed the question (Week 13): "Why does a moon go around Jupiter as opposed to the Sun, if the Sun has more mass?" After Audrey raises the issue of where Jupiter and its moons formed in the Solar System, Dylan suggests, "And because it formed around it, because it formed around it, or maybe it's because Jupiter is like farther away from the Sun—" and clarifies that the moon in question is "closer" to Jupiter. Shawn then adds to the discussion: "Since the [Jupiter's] moon is closer to Jupiter, Jupiter has more gravity than the Sun does since it's so close it overpowers it." During these discussions of orbital phenomena, Mrs. A encouraged students to respond to each other's ideas as they wrestled with complex phenomena that require the use of gravity.

Our analysis also suggests that students' application of the concept of gravity during whole class discussions as part of an investigation of planetary orbits, using the PhET computer simulation *My Solar System* [Weeks 11 and 12], may have supported a change in their ideas toward higher levels on the construct map. In the first lesson, the students manipulated mass, velocity, and position of planets in their orbits. In the second lesson, students used the previous day's investigation to determine factors that influence gravity and help explain stable orbits. Mrs. A asked the students to recall the three components of a stable orbit. After Nick suggests gravity, Mrs. A pressed the students to talk about what they need to have gravity, which leads to Jenna suggesting mass. Other students raise additional factors including initial velocity and distance from the Sun. The simulation offered students the opportunity to think about how mass and distance play a role in orbits. Mrs. A pushed students to move beyond simply describing gravity as a factor in what keeps planets in orbits toward using the variables that influence the force of gravity (mass and distance) in their explanations.

In summary, discussions where students wrestled with complex, open-ended questions about astronomical phenomena, and the application of gravity to explain orbital motion across multiple class periods may have shifted students' ideas to Level 3 and above as they applied gravity to explain orbits of the Moon and planets.

5.1.3 | Partial improvement trend: The balance of gravity and tangential velocity in orbital motion (into Level 4, but not Level 5)

The *balance of gravity and tangential velocity in orbital motion* trend describes students' ideas that changed from lower levels to Level 4 as these explanations included both the accurate use of gravity keeping planets in orbit and the nonnormative conceptualization that something prevents planets from crashing into the Sun, or the Moon into the Earth, often referred to as inertia. Students' conceptualization of inertia at this level was nonnormative in that they suggested inertia was similar to a force rather than a property of an object with a straight-line velocity that quantifies how strongly it resists the change from its straight-line motion to circular motion. Our analysis suggests that students had opportunities to learn about the role of inertia, as well as how tangential velocity can help explain orbital motion, through whole-class discussions focused on explaining Solar System phenomena and through discussions of thought experiments developed by the teacher. However, we conjecture that these opportunities did not support students' development of a full explanation for how inertia works in a type of balance with gravity (e.g., *Level 5*) as teacher-led discussions included both normative and nonnormative conceptualizations of inertia.

The concept of inertia was first discussed in a lesson on the tides. Mrs. A used terms such as "momentum" or "woah effect," while also providing examples of phenomena the students might be familiar with, such as riding an elevator, to help them make sense of inertia (Week 5). Later, we observed the students wrestling with how planets move in the Solar System during a lesson addressing the mass distribution of objects in the Solar System (Week 10). During a whole class discussion, students also began to question the relationship between inertia and gravity in planetary orbits, given what they had learned about the distribution of mass in the Sun and other planets (Week 10). Some students questioned how inertia relates to gravity, such as Brianna, who suggested that while the Sun's gravity pulls on the planets, inertia "pulls [the planet] back". Mrs. A encouraged other students to join the discussion:

Kelly	So, since the Earth and all the other planets have gravity too, which way are the planets' pulling? Are they, like is the gravity pulling towards the Sun [Mrs. A: Yes] or away. And … inertia is what is [Mrs. A makes a gesture as if pushing away from herself] making the Sun's gravity and the planet's gravity…?
Mrs. A	Inertia is … once something is set in motion in a straight line it wants to stay in a straight line forever, and ever, and ever, and ever, unless it hits [smacks her hands together] something else. But assuming it's not hitting something it wants to go in a straight line. But, gravity is also pulling us towards the Sun so instead of going off and off in a direction away from the Sun and instead of going into the Sun because gravity is not overpowering us, the gravity of the Sun is not overpowering us, we keep going and turning and instead of going straight and instead of going into the Sun, we've got this balance between the two that keeps us in orbit.

During Kelly's initial question, Mrs. A gestured as if to suggest inertia moves planets away from the Sun but this is followed by a normative description of the notion of inertia, or Newton's First Law, while also adding the force of gravity as the force keeping planets in their orbits. Kelly was still unsure of how a planet's gravity and inertial play a role in this explanation:

Kelly	The planet's gravity pulls them away from the Sun. The Sun's gravity overcomes that and pulls them towards that. And inertia [inaudible].
Mrs. A	You're thinking, I think that you're thinking that gravity from *other* planets might be pulling us, like gravity from the outer planets is pulling us out and the gravity from the Sun is pulling us in. Is that what you're asking?
Kelly	[nods]
Mrs. A	Although there is gravitational pull on everything that has mass, anything that would have mass has gravity so therefore would have a gravitational pull, it's not enough to be pulling us out there [gestures to the "outer Solar System"]. (…) Maybe a picture will help for all the others who didn't jump on board with the understanding train.

Mrs. A drew a diagram on the board (Figure 2).

In the diagram, the Earth is shown with two arrows representing the balance created between gravity (G) and inertia, as well as its orbit around the Sun (curved line). Mrs. A also describes the Earth as having an initial motion, due to its formation: "We call it inertia."

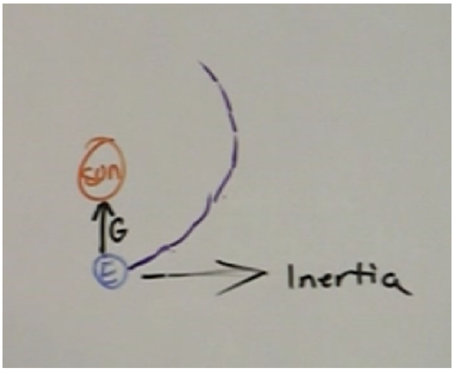

FIGURE 2 Mrs. A's drawing of the balance of inertia and gravity in the Earth's orbit [Color figure can be viewed at wileyonlinelibrary.com]

Mrs. A	But, if we had just inertia, see you later [gestures away from Earth], sayonara. You're not coming back. If we had just gravity [points to gravity arrow]? That's right, we wouldn't exist anyway because you would just be pulled into the Sun anyway.

As she continued to construct the diagram, Mrs. A struggled to explain the balance:

Mrs. A	Luckily, there is an equal amount of [gestures from Earth to the Sun] and force that's heading [gestures along inertia arrow] inertial force, er, I don't know [grimaces and mutters the “I don't know”]. Uhm, if inertia is making us go that way [gestures tangential along orbital path], and gravity is making us go this way [gestures towards Sun], it just happens to be not too much of a pull that way [gestures towards Sun] and not too much of a forward motion that way [gestures tangentially]. It just happens to be [puts her hands at a right angle together] not too much either way. And so that's what sends us instead [begins drawing curved path] kind of between those two points. And it is constantly pulling us this way [gestures along gravity arrow] and it is constantly pulling us this way [gestures along inertia arrow]. And keep going, and keep going, and keep going [drawing Earth's orbital path].

Mrs. A's representation is highly similar to those shown in astronomy textbooks describing this explanation. And she conveyed the way each component works together to produce a curved path about the Sun. However, she struggled to not equate inertia with a force rather than the tendency for motion. Further, the students did not have an opportunity to *use* this explanation until a lesson 2 weeks later, when they used the *My Solar System* PHeT computer simulation.

When investigating orbital motion using the *My Solar System* PHeT simulation, students manipulated the factors that influence gravity (varying position, also the Sun and planet's mass) and the initial velocity of the planet, thus, controlling inertia (Week 12). Early in the lesson, Mrs. A tried to help the class learn about the concept of initial velocity (used interchangeably with the term inertia in the class), using the analogy of a gas pedal on a car. This analogy reinforces the inaccurate notion that inertia is a force. Later in the lesson, students discussed the factors they found to influence the stable orbits they produced. We discussed this exchange when discussing a previous trend (out of Levels 1 and 2) where the students and Mrs. A are *using gravity to explain orbits*. Mrs. A asked students to name factors that have an effect on producing a stable orbit. Students suggested mass, velocity, and distance. Mrs. A wrote their claim on the board, while stating: “Mass, velocity, distance need to be in balance for a planet to have a stable orbit.” The class discussion of gravity turned to include inertia as well:

Mrs. A	The same way here, if you're too close, it might suck you in. If you are too far away it might pull you away. If you don't have enough initial velocity, you might get pulled into the Sun. If you have too much, you're going to—[gestures away]. So on and so forth. So what evidence do we have? What is our evidence? What happened on your screen?
Connor	[inaudible]
Mrs. A	Yeah, so if they're not in balance our evidence is it either floats away or runs into the Sun. [She writes this on the board.]

Here, Mrs. A continued to discuss how gravity and inertia form a balance in stable orbits, she again suggests inertia acts as a force ("if you are too far away it might <u>pull</u> you away").

In summary, the simulation may have supported students' visually as they learned to balance a planets' velocity with the force of gravity; however, the discussion shifted toward the nonnormative notion that inertia is a force. We conjecture that this challenge, with both students and the teacher using the alternative description of inertia as a force, may explain the ways in which students expressed similar nonnormative notions of inertia in their post-interview explanations of orbits and thus, their placement in Level 4. Students were not provided a model of how to accurately discuss their observations of inertia's role in the orbital simulations and therefore, did not have support to engage in their own productive discourse around this challenging concept.

5.1.4 | Improvement trend: Shape of the Solar System (Level B to A)

The *shape of the Solar System* trend suggests that, after instruction, a majority of students expressed a more accurate description of the Solar System: relatively flat and the planets orbiting in the same direction. Our analysis suggests that a week-long investigation culminating in an evidence-based explanation describing the flat-nature of the Solar System provided meaningful opportunities for students to develop a description for this normative model of the Solar System.

Students began by gathering data on a planet using the *Starry Night* simulation, which identified constellations the planets traveled through over time (Week 8–9). In the process, students were able to see if their planet was near the ecliptic line, which Mrs. A described as a "flat plane" in the Solar System. To begin writing an explanation, Mrs. A led the students in discussing what their data told them about how the planets travel with respect to constellations. Next, the class used their data to write a collective explanation for the shape of orbits in the Solar System:

Claim: The planets travel on a flat level.

Evidence: The planets travel through all of the same 12 Zodiac constellations.

Reasoning: The planets travel on the ecliptic, an imaginary line, running through the Zodiac constellations.

We observed few explicit opportunities for students to learn that all planets orbit in the same direction. Instruction on this topic was one-on-one, as when Mrs. A told a student while using the *My Solar System* PheT simulation: "See if you can get them to go counterclockwise, so that it [the planetary system] resembles ours [Week 11]." Other times, Mrs. A made gestures in a flat-plane circular direction when describing orbits to indicate they all move in the same direction (Week 8).

In summary, the trend toward describing the Solar System as lying on a relatively flat plane may connect to students' extended experience discussing the use of evidence as they worked together, as a class, to develop a model of the Solar System. Though more limited, the teacher also supported the students in noticing that all objects orbit in the same direction through in-the-moment comments and the use of gestures. This more limited instruction, perhaps coupled with the simplicity of the concept, led to improvement in students' descriptions that all planets orbit in the same direction.

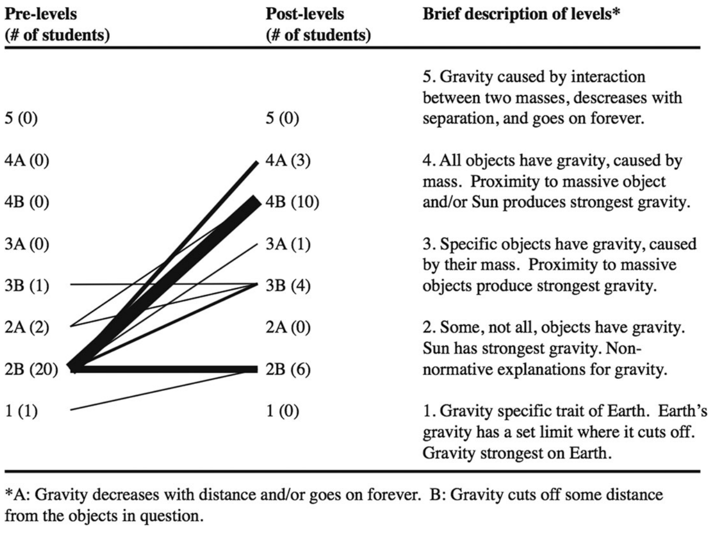

FIGURE 3 Change in students' ideas along the gravity construct map. The number of students whose ideas were measured at each level, before and after instruction is indicated parenthetically. The thickness of the line corresponds to the number of students whose ideas indicated that transition. A brief description of each level is provided for reference; full descriptions of each level appear in Supporting Information Appendix A

5.2 | The gravity construct map

Before instruction, most students' ideas (83%) were at level 2B for gravity (Figure 3). At this level, students' ideas included gravity as a property of specific objects. For example, students described the Sun, Earth, and Moon have gravity but gaseous planets like Jupiter do not. The main change in student ideas from preinstruction to post-instruction was a shift from Level 2B to Level 4B, as well as a small number of students whose ideas transitioned to Level 4A. The first area of improvement involves moving from Level 2 to Level 4 (*All objects have mass, more mass means more gravity*): moving from the belief that only some special objects have gravity to the idea all objects have mass, and therefore, all objects have gravity; further, a change from Level 2 to 4 moved toward the scientific conception more massive objects have more gravitational force. Most of the students provided descriptions of gravity that remained within the "B" modifier of the level (*Gravity cuts off*) and did not improve to the "A" modifier (*Gravity extends forever*), meaning the majority of students gave descriptions consistent with the nonnormative conception gravity.

5.3 | Gravity in the Solar System instruction

5.3.1 | Improvement trend: All objects have mass, more mass means more gravity (Level 2–4)

The *all objects have mass, more mass means more gravity* trend was connected conceptually to several instances of instruction. We conjecture that repeated conceptual reviews and opportunities provided for students to apply this concept to explain phenomena supported student learning, and thus improvement along the construct map. An example of the frequent conceptual reviews took place during the lesson on the tides. For example, Mrs. A asked "The Moon has mass, so Molly what does that mean that it has?" In response, Molly suggested "Gravitational pull." This continued as Mrs. A used guiding questions to help students to make connections between mass, gravity, and the Sun's large gravitational pull due to its high mass.

Another example of a conceptual review took place as the students and Mrs. A discussed their ideas about how to use inertia to explain the phenomenon of planets orbiting the Sun (Week 10). Brianna stated, "I know that when there's more mass there's more gravity. So, wouldn't the Sun have more gravity because it pulls the gravitational pull in for the planets? But then inertia pulls it back if it was…" As Brianna continued to wrestle with the notion of gravity and inertia other students joined in, offering their ideas about how gravity and inertia play a role in possibly explaining why planets stay in orbit. Mrs. A summarized one student's explanation suggesting that "although there is gravitational pull on everything that has mass," the amount of mass is important to consider and therefore, even though there are other planets far out in the Solar System, their gravitational pull is not enough to pull planets out away from the Sun. We found multiple opportunities for these conceptual reviews or discussions, often with Mrs. A repeating of "because it has mass, it has gravity;" these the use of verbal cues to connect mass and gravity frequently arose during while students used PHeT simulation to create stable orbits (Week 11 and 12).

These whole-class discussions around the topic of mass and gravity sometimes allowed students to delve in further and apply their ideas about gravity to new and more challenging phenomena. In one example, Mrs. A helped the class work through a student's question about how gaseous planets could have mass, and therefore gravity (Week 13). Jeff asked "Since Jupiter is bigger than Earth and has more mass, but Jupiter's made of gas and Earth is made of rock, so which one would have more gravity?" Mrs. A asks him to consider what gravity depends on. Jeff and the other students respond that gravity depends on mass. Mrs. A led students to suggest that Jupiter has more mass and therefore, Jupiter has more gravity.

However, this was not enough to convince Jeff. After Mrs. A led the class in a thought experiments about density, Jeff asked "But, isn't gas, like, weightless?" Mrs. A responded that "Everything that has something, has mass. And so, [Jupiter] just happens to have enough somethings put together." Jeff continues, suggesting that air is a gas and so must be weightless. Mrs. A suggests that it is a misconception that gas does not weigh anything.

After asking the students to read from their notes on the mass of Earth compared to the mass of Jupiter, Mrs. A continues the discussion:

Mrs. A	So, it [Jupiter] does weigh more than us [Earth].
Jeff	But it's a gas!
Mrs. A	I know! But there is a lot of it! [waves her arms about] And there's a lot of it in a confined area. So, it's, think of it as a thick gas. So, our gas here is maybe not very thick. So, if you take Jupiter and you pack in a lot of gas -
Jeff	But you *can't* -
Mrs. A	Teacher: But they *did*. It's called Jupiter.
Alyssa	It's the gravitational pull [gestures as if pulling].
Mrs. A	There's a planet, yes, there's a gravitational pull in Jupiter that's pulled in tightly, more tightly packed maybe, there's lots of gas in there and the gas that's all packed in there tightly in this really big circle, sphere, weighs a lot more than Earth. 317 times more, weighs a lot more than Earth. Mind blowing, isn't it?
Jeff	It's gas! Earth is rock. It doesn't make any sense.
Alyssa	(to Mrs. A) Do a comparison.

Alyssa's request ("Do a comparison") led Mrs. A to then lead the students through a second thought experiment, a comparison of a rock and a post-it note, where the rock is denser and more massive when you have the same size for the two objects. She compared the small rock to a large box of paper and asks which is more massive, to guide students, through prompts and questions, to see that a large amount of something less dense can result in a greater mass and thus still produce a greater gravitational force. This segment of instruction began with a student's question, but one that highlights a conceptual area that students often have difficulty understanding, and demonstrates the ways in which Jeff and the other students worked through reconciling their ideas with those Mrs. A asked them to consider.

In summary, these conceptual reviews and applications of the gravity-mass relationship to astronomical problems engaged students in working with the concept across multiple weeks of the curriculum. This repeated use and opportunity to apply the concept to new problems may have supported some students in improving along the construct map. However, nearly half of students' postinterviews continued express the idea only some objects in the Solar System have gravity (46%). Thus, additional types of opportunities for students to apply this concept to problems in astronomy may be necessary support these students, especially in ways that address the notion that all objects have mass and therefore gravitational pull and that allow students to use this concept beyond whole-class discussions that may not have engaged all learners equally.

5.3.2 | Limited improvement: Gravity extends forever (Level B to A)

Only four students (17%) provided explanations during their postinstruction interviews that included *gravity goes on forever* (Level A). This may result in part from the fact that we identified only a few instances during classroom instruction where the extent of gravity's influence was discussed and these did not resolve with a clear indication that gravity extends forever with diminishing strength. During a discussion of the balance between inertia and gravity, a student questioned the extent of Earth's gravity. Mrs. A began by stating the Earth's gravitational pull stops above our atmosphere (Week 10). But then, after asking what the Earth, because of its gravity, is pulling—Mrs. A started wondering why the Moon orbits the Earth. Multiple students participated in coconstructing the explanation that the Earth's gravity keeps the Moon in orbit, led to this exchange:

Mrs. A	(...) Gravity from Earth is pulling the Moon. So, there is some gravitational pull even past that little (...)
Jenna	There has to be enough [gravity] between the -
Connor	Yeah, here has to be enough between the Moon to keep it [more inaudible] [Week 10]

This discussion involved numerous students engaged alongside the teacher in coconstructing the idea gravity must go beyond just the Earth's atmosphere as they reasoned through the evidence.

A second example occurred during a discussion of the formation of the Solar System [Week 11]. A student asked if inertia could be gravitational pull from another star, and Mrs. A explains why another Solar System could not affect our Solar System. Mrs. A then asked about the heliopause,[4] leading the students to conclude this is the end of the Sun's gravitational pull.

In both instances, the discussion was driven by students' questions; while the subsequent discussions engaged students with the concept gravity is weaker at a distance, both discussions raise the nonnormative conclusion concerning the force of gravity. Thus, more data is needed from instruction that explicitly supports the concept that gravity decreases with distance but extends forever, to draw conclusions about how instruction can support this portion of the LP.

6 | DISCUSSION

We proposed three main goals for this study: (a) provide evidence for the validity of the LP by testing its use as a measurement of change in students' ideas in the context of a middle school astronomy unit, (b) describe instruction associated with increasing sophistication up the construct map levels, and (c) uncover contingencies between the construct maps. Addressing these goals has led us to a more nuanced, evidence-based description of the Solar System LP. This description is contextualized among these students, teachers, and an instructional storyline. We will discuss the challenges of contextualization in the use of LPs when engaged in LP-based research.

6.1 | Evidence for the validity of the LP

Our prior research analyzing student interviews clarified the nature of the levels (Plummer et al., 2015) while the present study provides evidence that this LP can be used to describes some of the improvement in students' ideas after participating in a curriculum designed for this big idea. The dynamical properties and gravity construct maps were used to identify trends in how students' ideas changed across a 14-week astronomy curriculum. Many students' ideas shifted from showing limited descriptions of planetary orbits to using a combination of gravity and a nonnormative inertia concept to explain the orbits phenomenon. The majority of students also expressed ideas that changed from believing only some, special objects in the Solar System produced a gravitational force to describing all objects with mass as having gravity.

We provide evidence of how these construct map levels can be used to measure patterns of change in student thinking across a middle school curriculum; this provides initial evidence for the validity of the Solar System LP. We aligned the construct map descriptions to student ideas *and* considered how a change in student thinking is dependent on students' experiences in a particular curriculum context as an important piece of our validity argument. Slopegraphs were used as evidence of trends in how students' ideas changed across the astronomy unit. These trends show the cumulative effect of students' experiences with the curriculum; a possible limitation of this evidence is that we were only able to make these measurements before and after instruction rather than over multiple time points. However, this evidence is helpful in making sense of how student thinking may improve in middle school and allows us use these patterns in student ideas to offer suggestions for future research on LPs and instruction.

Metz (2009) argues LP research should help us understand what is possible for students to learn under more optimal instructional conditions, pointing out the limitation of standards documents grounded in research on current instructional opportunities. Instruction in the present study went beyond the “status quo.” Rather than using traditional instructional practices, Mrs. A included characteristics of reform-based education shown to facilitate student learning. The curriculum was designed around a 14-Week CSCS unit toward the big idea of the Solar System's formation (Roth et al., 2011). Instruction included several long-term investigations where students actively gathered data to answer questions about the nature of objects in the Solar System and how they moved as a system. Students were supported through small group and whole class discussions using data as evidence in conjunction with physical models and computer visualizations. Thus, we suggest the evidence presented here points to aspects of “what is possible” for students to learn in a reform-based curriculum; however, as we discuss below, limitations of the instruction also shaped how students' ideas improved.

6.2 | Progress, challenges, and instructional support along the LP

Rogat et al. (2011) recommend LPs be considered “teaching and learning progressions” rather than “learning progressions” alone, to highlight the importance of the instructional sequences are tied to improvement from one level to the next. Our work is exploratory, as we can only infer some connections between a set number of trends in how students' ideas changed and the affordances identified in the instruction they experienced. This limits the extent to which we can draw detailed conclusions about how specific instruction supported specific transitions up the learning progression. We examined whether patterns we observed in changes in LP levels and how these may relate to challenges in student reasoning or limitations in instructional opportunities for students (instructional support for change in ideas on the LP is summarized in Supporting Information Appendix A). From this, we draw conclusions on possible recommendations for instruction within this LP and point to areas where further research is needed.

Instruction that supports improvement in student explanations in the Solar System LP will need to support students as they learn both the descriptive elements of orbital motion and the underlying physics that explains this motion. Students' experience investigating the nature of orbits, using both physical representations (modeling in the classroom) and computer simulations, supported their ability to accurately describe planets as orbiting in the same direction and on a relatively flat plane. This suggests the descriptive component of the LP can be supported through investigations that engage students in constructing and engaging in dialog around physical and computer-based models of orbits.

Changes observed in where a student's ideas were placed along the dynamical properties construct map was not hindered by their understanding of gravity but by how they used an object's tangential velocity to explain the balance in that object's orbit. We conjecture that students learned that gravity is the force that keeps planets from escaping their orbits through multiple opportunities to discuss gravity's role in phenomena in the Solar System; this was particularly salient in a computer simulation where students manipulated variables relating to gravity (mass and position). The use of the concept of gravity as an explanatory factor in orbits was a commonly raised construct in the discourse, rather than the subject of a particular lesson. This suggests that repeated opportunities to discuss ways to apply the concept of gravity to new phenomena during class may support students to adopt the notion of gravity as a force that keeps objects in orbit.

Limited improvement was observed on students' application of the role of tangential velocity in orbital motion. Instead, students described inertia as a “force” that counteracts gravity in their explanations. The instruction did not always engage the students with this concept effectively or, at times, accurately. The students were provided an interactive, visual experience with orbital motion—in particular, with observing the effects of changing initial velocity—through a computer simulation. This positive starting point could potentially lead to productive discussion around the balance between having the right tangential velocity to balance the gravitational force experienced at a certain distance from the Sun. However, the teacher's additional support included the use analogies and explanations that sometimes aligned with the scientific conception, but at other times, reinforced the nonnormative conception of inertia's role as a second force. Thus, we are not able to make specific conclusions about how instruction can help students express ideas at higher levels of this construct map.

However, Velentzas and Halkia (2013) found some success with using the Newton's Cannon thought experiment to support Greek high-school students' understanding of the balance between inertia and gravity in explaining orbits. Newton proposed that we imagine a cannon atop a very tall mountain. If a cannonball is launched with sufficient initial velocity, it will fall due to the Earth's gravity at the same curvature as the Earth's surface, and thus take up an orbit. Velentzas and Halkia found that while students eventually accepted that, with an appropriate velocity, the projectile would take up an orbit, students were initially hesitant to accept that such an object could be launched into orbit about the Earth. We suggest that future research consider how the Newton's Cannon thought experiment could be used to support middle school students' use of velocity as a component of explaining orbits. This, in combination with an additional conversation about their observations of the planet's velocity in the PHeT simulation and modeling of scientific language to use to construct the scientific explanation, may support additional improvement along the LP.

Most students' postinstruction explanations included the idea that all objects have a gravitational force caused by their mass and proximity to a massive object increases the force of the gravitational pull. The nature of gravity as a force was woven during the whole-class discussions throughout the coherent science content storyline. The teacher frequently connected objects' mass to their force of gravity during questions and discussions with the students. The students' application of gravity as they explained changes in planetary orbits in the PHeT simulation may also have supported this improvement as measured by the construct map. We recommend that these strategies, ongoing teacher-initiated conversation in which the connection of gravitational force, mass, and distance is applied to the explanation of phenomena in the astronomy curriculum, could form a starting point for supporting students in the domain. The level of sophistication of these 6th grade students' explanations for gravity allowed them to begin to explain some of the astronomical phenomena they discussed in class, but does not represent a deep, scientifically accurate explanation of gravitational force that students might achieve through additional instruction in secondary school.

In particular, students struggled with how all objects (e.g., gaseous objects) can have mass, and therefore gravity, and both the students and teacher wrestled with the extent of gravity's force between objects. The limited improvement we observed in these areas suggests additional, explicit methods of engaging students with these fundamental aspects of gravity was needed. And, while an extensive body of literature has explored students' ideas about gravity (Kavanaugh & Sneider, 2007), fewer studies have explored productive instructional methods in this area. Lelliott (2014) considered how South African 7th and 8th grade students' (*N* = 26) ideas about of gravity changed after visiting a science center. Before the visit, few students thought gravity would be high on Jupiter (17%) while about half thought it would be low (50%). After the visit, this improved to 50% who said gravity would be high on Jupiter. This shift in thinking about gravity may relate to students' experience with an exhibit in which students engaged with Coke cans each weighted to be proportional to what the can would weigh on different planets. Their findings may point to the need for more research on how physical experiences may help students develop a deeper explanation for how all objects can have gravitational pull. Bar, Sneider, & Martimbeau (1997) investigated how studying orbital motion using Newton's Cannon thought experiments could help the U.S. students in 6th grade (*N* = 48) learn that gravity acts beyond the Earth's atmosphere. However, after instruction, only 48% of students said gravity acts in space, where there is no air. Though such a strategy may help explain orbits, more research is still needed to understand how to support this challenging concept of how gravity acts at a distance.

While we have found connections between student experiences in this astronomy curriculum and the trends in improvement along the Solar System LP, our findings also point to the importance of contextualizing LPs in curricula. In other words, our findings do not suggest the LP concludes with middle school students only achieving to a certain level along the LP because our analysis identified both areas of the instruction that supported improvement and areas of potential weaknesses in its design that could potentially explain limitations in student improvement. The work of understanding students' capacity to achieve in this domain will require additional iterative research that considers the complexities of physics in how students reason about astronomy at the middle school level and what other innovative strategies might be employed to support that reasoning.

6.3 | Contingencies and further refinement for the LP

We proposed a hypothetical Solar System LP composed of four construct maps through the analysis of student explanations from clinical interviews conducted with a cross-age sample (Plummer et al., 2015). In this paper, we closely examined two of these construct maps and considered evidence for possible contingencies between construct maps that clarify their relationship (Shea & Duncan, 2013). First, based on our finding that students use a relatively low-level (on the construct map) descriptions of gravity in their explanation for orbital motion, the link between the gravity construct map and the dynamical properties construct map sits relatively low on the LP. Second, our findings suggest there is a missing dimension, or construct map, in our conceptualization of this LP—building toward inertia. It was students' developing understanding of the relationships between force and motion that limited the changes in their explanations; thus, the links between a potential, to-be-developed, inertia construct map and the dynamical properties construct map seems to be placed higher up on the LP.

Alonzo and Steedle (2009) describe a force and motion LP based on middle- and high-school students' responses to ordered-multiple choice items. The upper anchor describing how forces change an object's motion is a more advanced way of conceptualizing the reasoning students need to apply to explain orbital motions: "[The s] tudent understands that the net force applied to an object is proportional to its resulting acceleration (change in speed or direction) and that this force may not be in the direction of motion" (p. 403). However, the levels building up to this upper anchor do not directly match the type of reasoning students were using in our study to explain orbital motion. This suggests more work is needed to understand how students develop increasing sophistication in their use of inertia in both Earth-based and astronomical contexts. It also points to the importance of looking at the learning context, both in terms of the field of study (e.g., Solar System astronomy) and the curriculum itself, as the level descriptions in a LP are dependent on the nature of the curriculum and the assessment design.

We also raise a concern on the way standards documents emphasize gravity but not tangential velocity in explaining orbital motion (Flarend & Palma, 2013; Plummer et al., 2015). Pennsylvania state science standards (where this study was conducted) as well as the *Framework* and Next Generation Science Standards (NGSS Lead States, 2013) focus on gravity's role in orbital motion but lack an emphasis on the role of planets' initial velocity and ignore the importance of understanding the balance between gravity and inertia in explaining orbits. Our research suggests most students did not find using gravity to explain orbital motion to be difficult; rather, it was understanding the role of initial velocity that was the greater challenge. Leaving this out of standards documents may result in teachers and curriculum developers ignoring the aspect of instruction where students need the most support.

We found that many students transitioned to levels on the LP that, though frequently not the upper anchors, could be considered necessary points of transition toward their development of the more scientifically accurate explanation described by the upper anchor. Sevian and Talanquer (2014) suggest potential energy wells can serve as an analogy for regions where students' ideas have relative stabilities and thus can serve as stepping-stones in a learning progression. Achieving a notion of "balance" in orbital motion, for example, even with its inaccuracies, may be a helpful notion that could be built upon in later instruction where students further delve into the mechanics of orbits.

7 | CONCLUSION

We provide initial evidence for the validity of the Solar System LP levels, insight into the nature of instruction that supports student learning in the domain, and identify potential connections between the Gravity and Dynamical Properties construct maps. The learning trajectories show the potential of what students can achieve in this domain and instructional context, but also to begin to identify areas where further research is needed. By considering the limitations of student improvement and the instruction provided, we see ways future research can extend our understanding of how to support student learning of physics in astronomy contexts and elaborate on the hypothetical connections made with other LPs proposed in this paper. Our work contributes to limited research exploring these potential connections across LPs (Shea & Duncan, 2013) that will strengthen our understanding of how to enact the *Next Generation Science Standards* (NGSS Lead States, 2013).

While several LP authors advocate for describing instructional components that can move students from one level to the next as part of the LP design (e.g., Krajcik et al., 2012; Rogat et al., 2011; Smith et al., 2006), ours is one of only a few studies to have explicitly shown how these instructional components can be part of an empirically tested LP. Merritt and Krajcik (2013) described research on a LP for the particulate nature of matter in a middle school unit. Their analysis suggests progress was supported through a sequenced approach to learning particle theory, as well as opportunities to gather evidence from phenomena to create and critique models. Merritt and Krajcik added an additional layer to their construct map levels describing instructional strategies that could move students from one LP level to the next. Plummer and Maynard (2014) developed a construct map for reasoning about the seasons based on pre/postassessments of middle school students. Analysis of opportunities to learn key concepts and relationships during their seasons curriculum was used to offer possible explanations for trends observed in student progress as measured by the construct map. The resulting analysis offered descriptive explanations for aspects of instruction supporting progress, but also identified gaps in the curriculum and places where additional support was needed. Thus, similar to the present study, the instructional supports for this LP are largely suggestive of possible "key instructional components" due to the contextualized nature of the analysis as well as questions raised about limitations in the instructional design. More LP research is needed that illustrates potential connections between instructional design and student progress.

Our study has certain limitations that may point to the need for further research in this area. Most students did not provide explanations placed at the upper anchors of our construct maps; this could be explained due to the nature of instruction. Thus, a limitation was that instruction was not designed to fully support students in ways that helped them think about the upper anchor level explanations, despite the fact that this teacher dedicated approximately 15 weeks of instructional time to astronomy. Future research where a teacher trained to identify and build on the ways students reason at lower and intermediate levels of the construct maps may help us learn more about strategies to support students changing their ideas toward more sophisticated levels on the LP. However, this leads us to an alternative question we have wrestled with in the context of this study: What is an appropriate upper anchor for middle school students and what does the development of this LP mean when it has been tested in the context of a middle school curriculum? Upper anchors can represent societal goals for students (Corcoran et al., 2009); as we conducted this study in a middle school classroom, it is relevant to question whether the upper anchors suggested here are within reach of middle school students (and their teachers). The upper anchors of these two construct maps go beyond what is described for middle school students in state and national standards. For both construct maps, most students' ideas did not reach the upper anchor. Yet, for many students, middle school is the last time when astronomy will be formally studied in school (e.g., Plummer & Zahm, 2010). Thus, our goal in studies such as this is to better understand what children are capable of learning with appropriately designed instruction, rather than relying on standards based on a simple unpacking of content or limited research on student ideas in the context of status-quo instruction (Metz, 2009). LP research that uses evidence of how students' come to understand and apply big ideas of science, and critically examines the instructional conditions in which that evidence was gathered, has the potential to shape how standards are implemented through a curriculum designed to support students in evidence-based instruction.

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ENDNOTES

[1] The teacher's name and all student names are pseudonyms.

[2] More information on the software can be found at http://astronomy.starrynight.com/ and http://phet.colorado.edu/en/simulation/my-solar-system.

[3] The interview data used in this study were part of a larger set of data previously used to define the learning progression as described in Plummer et al. (2015).

[4] Scientists define the Sun's heliopause as the boundary where the solar wind interacts with the interstellar medium.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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