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Student Ideas about Kepler's Laws and Planetary Orbital Motions

Ka Chun Yu
Denver Museum of Nature & Science, Denver, Colorado, 80205
Kamran Sahami
Metropolitan State College of Denver, Denver, Colorado, 80217
Grant Denn
Metropolitan State College of Denver, Denver, Colorado, 80217
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Abstract

We present the analysis of oral interviews with 112 undergraduate nonmajor students during the first week of a General Education Introduction to Astronomy class before they had received any instruction. The students were asked questions relating to Kepler's three Laws of Motion, as well as their understanding of what keeps planets in orbit around the Sun. The most common misconception found in about three-quarters of the interviews is the belief that planetary orbits about the Sun are highly elliptical. Less common ideas include a mix of circular and highly elliptical orbital shapes. Many students have conceptions consistent with the Kepler's Second and Third Laws of Motion, and the ease with which these models are adopted by students may suggest some ways to teach these concepts via analogy. The types of ideas about orbital shapes and orbital behavior may originate in common depictions of orbits often seen in print and on the Internet.

1. INTRODUCTION

Previous research exists on how students understand gravity; see, for instance, the reviews by Kavanagh and Sneider (2007a, 2007b). The direction of gravity has been linked with naive understanding about the shape of the Earth (Nussbaum and Novak 1976; Za'rour 1976; Mali and Howe 1979; Sneider and Pulos 1983; Baxter 1989; Vosniadou and Brewer 1989, 1992, 1994). Many other naive notions about gravity have been documented including misconceptions about its medium of transmission and strength (Gunstone and White 1980; Watts 1982; Ruggiero *et al.* 1985; Piburn, Baker, and Treagust 1988) and its effects on the motions of planets (Smith and Treagust 1988). Misconceptions about forces and motion in general are also common (e.g., Whitaker (1983), McCloskey, Washburn, and Felch (1983), Halloun and Hestenes (1985), Maloney (1988), and Hestenes, Wells, and Swackhamer (1992)).

The vast majority of studies on the understanding of planetary orbits concentrated on K-12 students' conceptions of the configuration of the Earth-Moon-Sun system, i.e., what was orbiting what, and their relationship to observed cycles in the day and night sky. Perhaps the first paper to examine children's rudimentary beliefs about the Solar System was work involving the interviews of 32 school children in grades 3 and 6 (Jones, Lynch, and Reesink 1987). School children's mental models fell into roughly five different categories of spatial relationships between the three bodies. The first three are geocentric in nature: 1) The Sun and Moon moving toward and away from the Earth in tune to the day and night cycle; 2) the Earth spinning on its axis while the Sun and Moon remain stationary; and 3) the Sun and Moon orbiting an Earth that was either static or spinning. The remaining two models were heliocentric: 4) Both the Earth and Moon orbiting the Sun and finally 5) the scientifically correct model of the Earth orbiting the Sun, while the Moon orbits the Earth. The students found predictive value with all of the incorrect models, both geocentric and heliocentric. In the first case, the Sun provided light during the day, while the Moon provided illumination at night. The next two models could explain the diurnal cycle with motions of the Sun and Moon and/or the spinning of the Earth. The fourth scientifically incorrect heliocentric model had the additional benefit of providing an explanation of what happens over the course of a year. However, even for students who picked the last model, there was confusion about which if any of the bodies were spinning on its axis. Even when a pupil stated that the Earth spun, he or she did not know how often it rotated within a year or how long it took for the Moon to orbit the Earth.

These results have been replicated in other studies. Roald and Mikalsen (2001) found similar mental models, if not more varied, in their details in deaf and hearing pupils in Norway. Samarapungavan, Vosniadou, and Brewer (1996) discovered similar results in their sample of 38 Indian school children, although their cosmological models were informed in part by the folk models accessible to the children. The first model of Jones, Lynch, and Reesink (1987) (Sun and Moon staying on opposite sides of the Earth) has also been found by Parker and Heywood (1998), Adams, Doig, and Rosier (1991), and Sharp (1996). Dunlop (2000) found a similar belief in two children (out of a sample of 67 with ages between seven and 14) that the Earth orbits in a figure-eight pattern, first going around the Sun during the day, and then proceeding to circle the Moon at night. The idea that the Earth orbits the Sun daily also has been observed in school children in England (Osborne *et al.* 1994) and New Zealand (Crookes and Flockton 1996; Noble 1998; Dunlop 1999). The conceptual model of a Sun orbiting the Earth daily has been found in school children (Baxter 1989, 1995 (p. 155), 1998 (p. 139); Adams, Doig, and Rosier 1991; Sharp 1996) as well as teachers (Parker and Heywood 1998). Even for college students taking an introductory earth science course, one study found that a significant minority (40%) could not correctly sketch the orbital relationships between the Earth, Moon, and Sun (Delaughter *et al.* 1998).

Ideas about the actual shape of orbital trajectories and details of the velocities of objects in motion have not been studied to a great extent. Sadler (1992) quizzed 1414 high-school students on a variety of astronomy topics, one of which was the shape of the Earth's orbit: "…which looks most like the Earth's path around the Sun?" Students taking the quiz could select from five multiple-choice answers. The first, a circular path with the Sun at the center, was picked by 49% of the students. The next most frequent choice was a highly elliptical orbit with the Sun located near one end of the ellipse, chosen by 28% of the students. The third most common answer was selected by 14% of the students: A circular orbit with the Sun displaced from the center. Eight percent of the students chose the fourth answer, a highly elliptical orbit with the Sun *outside* of the orbit. One percent picked an orbit that was shaped like a figure-eight or an analemma, with the Sun located in the larger of the two loops.

Student preference for a highly elliptical orbit for the Earth, with the Sun displaced from the center, could be attributed to the belief for the cause of the seasons (Furuness and Cohen 1989). For students who believe that the Earth warms and cools because of its proximity to the Sun (Touger 1985; Baxter 1989; Trumper 2001), it would not be surprising to learn that their personal cosmogony has a variable Earth-Sun distance. However, Sadler found that this question about orbits was a poor discriminator of a student's overall success in answering questions on the astronomy test. Although roughly half the students answered this question correctly, their success on this question did not correlate with success on the rest of the test questions. In fact, there was a slight increase in the number of students picking one of the multiple-choice distractors with increasing final test score. Sadler believes this might be due to the more knowledgeable students having heard about the Earth's eccentric orbit but who did not realize how small the eccentricity really is.

2. THE ALIVE RESEARCH PROJECT: KEPLER'S LAWS AND ORBITS

The interviews described in this paper were performed as part of the Astronomy Learning in Immersive Virtual Environments (ALIVE) project undertaken at the Denver Museum of Nature & Science and Metropolitan State College of Denver (MSCD). This study evaluates the effectiveness of real-time astronomy visualization software running in digital planetariums for teaching college undergraduates. The interviews were front-end evaluations performed to gauge the prior knowledge of students entering an introductory astronomy course at MSCD and to categorize their most common misconceptions so these may be addressed in the pedagogic scheme. In addition to confirming documented misconceptions found by previous researchers, we hoped to discover new erroneous beliefs not previously studied.

Among the topics covered in the interviews, Kepler's Laws of Motion and the structure of orbits had not been examined as extensively, if at all, by previous researchers. We therefore had an opportunity to take a fresh look at current student ideas about several astronomy topics covered at the undergraduate level.

3. INTERVIEW PROCESS

We interviewed 112 undergraduate students enrolled in MSCD's ASTR 1040 astronomy classes in the Fall 2005 and Spring 2006 semesters. Two sections of this single-semester astronomy class were taught each semester; these sections gave an introduction to the subject covering topics from the Solar System and extending out to the stars and galaxies. On the first day of class, students were informed by their class instructor of the ALIVE project and were encouraged to sign up for the 30-min interview, with further incentive provided by a $10 honorarium. Students could sign up for slots distributed throughout the first week and into the first 3 days of the second week of classes. The instructors of the classes focused on historical astronomy during the first week of classes, and hence, there was no overlap between the lecture material discussed in the classrooms during this time and the topics covered in the interview.

Sixty-three students from Fall 2005 classes were interviewed August 24–31. Forty-nine students from two Spring 2006 classes were interviewed January 20–30. The interviews occurred before the reclassification of Pluto as a dwarf planet by the International Astronomical Union in September 2006. As a result, when mentioned at all by the students, Pluto is included as one of the planets in the Solar System. The recorded interview audio from all of the students, including questions from the interviewers and answers from the respondents, totaled 44 h 21 min. A total of 7 h 23 min of interview time was spent on the questions of Kepler's Laws and orbits, or an average of 17% (or 5 min) of the total interview time for each student. Two independent codings of the interviews were performed by the authors. The interview protocol is further described in the Appendix.

The interview questions were divided into seven different astronomical topics, with the topic of Kepler's Laws and orbits fourth out of seven. The questions in this section asked about the orbital motions of planets in the Solar System and were specifically designed to be open-ended, free of jargon and nonleading:

Q15: Tell me what you know about planetary orbits? (The alternate, "What is an orbit?," was used if the student professed no knowledge about planetary orbits at all.)

Q16: What do you know about orbit shapes? Draw a couple of different orbits. (Alternate follow-up: "Okay, how would that look if you draw it?" Students were provided with paper to sketch their answers.)

Q17: What do you know about orbit speeds? (The alternate, "What can you tell me about the way planets move?," was used if the student professed no knowledge about orbital speeds.)

Q18: Why do the planets move the way they do?

The questions were designed to see what student ideas existed about Kepler's three Laws of Planetary Motion. Typically, these are stated as follows:

1. Planets orbit the Sun in elliptical orbits, with the Sun at one of the foci of the ellipse.
2. The planets sweep out an equal area in equal amounts of time as they travel in their elliptical orbits.
3. When comparing two planets in orbit around the Sun, the ratio of the squares of their periods is equal to the ratio of the cubes of their semimajor axes, or

$$P_1^2/P_2^2 = a_1^3/a_2^3$$

Kepler's First Law of Motion states that the planets orbit in elliptical paths with the Sun at one focus. Each planet has its own orbit. Although Pluto does get closer to the Sun than Neptune during one portion of its orbit, their two orbits do not actually intersect. (At the time of the interviews, the debate about Pluto's status as a planet had not become widely known to the public.)

We first wanted to elicit student ideas about the shapes of planetary orbits since nonscientific ideas about orbital shapes had figured prominently in Sadler's (1992) study. The first question was written to be general enough to determine if the student knew what an orbit was. If the student did not understand that planets moved in fixed and closed trajectories around the Sun, then it would not make sense to ask the next question about the shapes of orbits. However, among our student interviewees, only six of them did not know enough about the concept of orbits to be able to provide an answer to question Q16 with a drawing of an orbit around a central body.

One key element in the drawings that students created is, of course, perspective. We are aware that if a drawing was made of an orbit that appeared as a flattened ellipse, possibly more than one interpretation could exist in the mind of the student. The student could believe that the orbit was indeed highly eccentric, or "cigar-shaped." Alternatively, the student could be drawing a nearly circular orbit from an oblique angle, a perspective that would give a nearly circular orbit a flattened appearance. In the cases in which a symmetrically, flattened orbit was drawn, the interviewer asked the student if the view was perpendicular to the plane of the orbit or if it was closer to edge-on.

Kepler's Second and Third Laws deal respectively with how a planet's velocity varies in its orbit and how the velocities of planets at different distances from the Sun vary. Both of these topics are covered by the queries initiated as question Q17. If a student drew an orbit that was clearly noncircular, interviewers were trained to ask if the planet's speed varied at different points in the orbit, pointing to parts of the trajectory both near and far from the Sun.

Unless the student was already well versed in astronomy or physics, it would be unlikely for her to be able to cite Kepler's Third Law in a form similar to the formula shown above. Therefore, after querying the student on the speed of a planet within an orbit, the interviewer asked her what if anything she could say about the speeds of the planets in different orbits. To ensure that more than one planet could be referred to, question Q16 specifically asks the student to draw multiple planets and their orbits.

Finally the last question Q18 was used to see if students had the basic understanding that gravity was responsible for planetary motions in the Solar System. Note that the question does not refer to the term gravity itself, nor is the Sun mentioned, to avoid leading the student.

4. INTERVIEW RESULTS

4.1. Kepler's First Law Results

All but two of the 112 students interviewed gave some form of answer to the first question about orbital shape. (These and the other interview results are summarized in Table 1.)

Additionally, two of the interviews were not included in the subsequent analysis because it was decided during the coding that the interviewer gave too much information to the student during the questioning. Eleven of the students (10%) gave very confused answers, either indicating a wildly divergent understanding of the concept or not understanding the question. For instance, one student confused orbits with planetary rings. Another talked about planets moving around both the Earth and the center of the galaxy. One student spoke only about the Earth "spinning" and moving in any number of directions. The student confused about rings and orbits, however, provided a plane-on drawing showing multiple planets with individual near-circular orbits around a clearly labeled Sun. Although individually interesting, these answers did not appear to correlate, even broadly, to any other answers and therefore defied classification.

Thirteen (12%) students used only the word "circle" or "circular" to describe the orbits. No other descriptive terms were used.

A large majority of the students (70%) described the orbits as not being circles. Fifty-one (46%) of these students understood that orbits deviated from a pure circle ("circular-ish," "not necessarily circular," "not perfect circles"). They used terms like "elliptical," "ovoid," "egg-shape," "oblong," "oval," and even "eye-shaped," with oval being the most common (specified by 33 or 30% of the students). Twenty-six (24%) of the students described the orbit only as elliptical with no reference to any other term except for circles. When circles were mentioned, it was in the context that the orbits were decidedly *not* circles ("elliptical as oppose to circular," "elliptical, not circular," "they're not perfect circles," and "they're typically not a perfect circle"). Students familiar with the word ellipse or elliptical might also add oval as another descriptor.

Table 1. Student ideas about Kepler's laws based on open-ended interviews with $N = 112$ undergraduate students. Responses from students who were cued with possibly leading information from the interviewers are not included

		Responses	
Topic	**Student Belief**	***N***	**%**
Kepler's First Law			
Orbit shapes	Orbits are not circles; they deviate from a circle (e.g., oval, ovoid, oblong, egg-shaped)	51	46
	Orbits are elliptical	26	24
	Orbits are circular	13	12
	Confused understanding	11	10
	Orbits are a mix of elliptical and circular	9	8
Kepler's Second Law			
Speed of a planet in its orbit	No answer	61	54
	Speeds are constant	23	21
	Planets move faster when closer to the Sun, slower when further away	17	15
	Confused understanding	8	7
Kepler's Third Law			
Speeds of planets in relation to their distance from the Sun	Planets orbiting closer to the Sun move faster; those orbiting farther move slower	47	42
	No answer	21	19
	Planets orbit at different speeds	12	11
	Confused understanding	8	7
	Farther planets have larger orbits (did not answer interviewer's question)	6	5
	Speeds are constant	5	4
	Speeds are dependent on size or mass of the planet	4	4
	Speeds are dependent on mass, distance, and other factors	4	4
	Longer path of orbit implies a longer year (did not answer interviewer's question)	4	4
Explanation for planetary motion	Sun's gravity or pull from Sun	37	33
	No answer	19	17
	Confused understanding	17	15
	Sun's gravity plus some aspect of the planet (e.g., its mass, density, centrifugal force, magnetic fields, distance, natural versus artificial satellites, number of moons, and presence of rings)	14	13
	Gravity (no mention of the Sun)	12	11
	Aspect of the planet only (e.g., its composition, atmosphere, mass, size, and position)	8	7
	Expelled gases	2	2

In their drawings, twelve students (11%) made drawings of orbits that were highly eccentric: At a minimum of $e = 0.8$ but often $e >= 0.9$ (Figure 1). Nine students who drew planetary orbits were not asked by their interviewers to verbally describe their drawings nor to explicitly explain their ideas of orbital shapes. As a result, although their drawings suggest that these students probably had similar oval or elliptical conceptions of orbits, this cannot be confirmed.

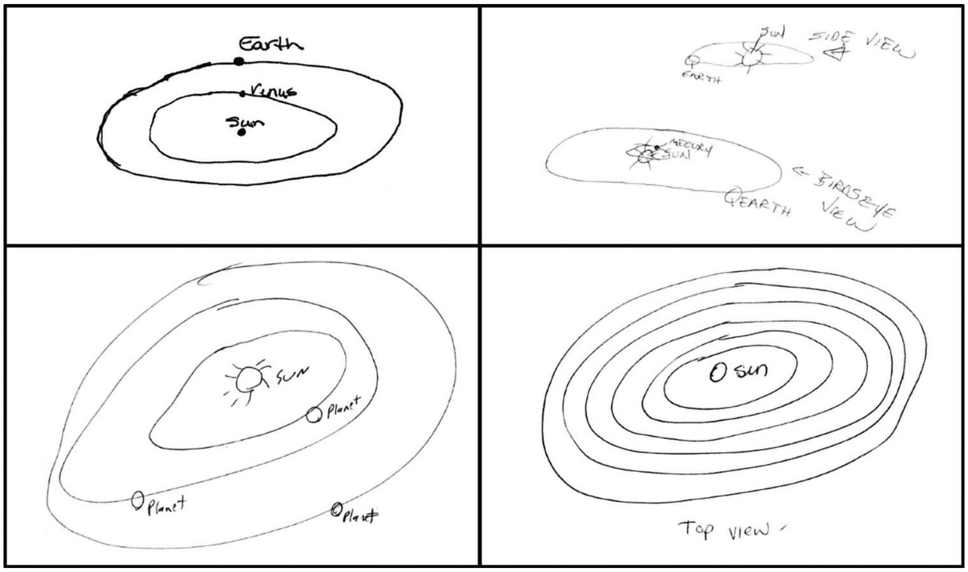

Figure 1. Some examples of the highly elliptical planetary orbits drawn by the students interviewed for this study. Note that the students were explicit in the interviews that these orbits are as eccentric (or oblong or oval) as shown. Hence, we are not seeing a side or "profile" view. In the top right drawing, the student has drawn a side as well as a top-down view, with both showing very elliptical orbits

Finally, nine (8%) of the students described the Solar System with both circular and elliptical orbits. One of these interviewees gives a description that is nuanced enough to reflect the true shapes of planetary orbits in the Solar System:

> Q: And anything about the shape?
>
> A: Shapes? As far as, what, the planets?
>
> Q: Shapes of orbits.
>
> A: Oh, shapes of orbits. Yeah. Well, circular, but I think, I don't know, well maybe a smidge. I'm not saying circular is not being perfect. If I say circular I know, like, they're not a hundred percent perfect.
>
> Q: Uh-huh.
>
> A: So maybe elliptical.
>
> Q: Elliptical. Slightly elliptical.
>
> A: Yeah. I know they're no perfect circle.
>
> Q: Slightly circle. Slightly elliptical. *(laughs)*
>
> A: Sure. It's in between.

However, most of the students describing a mix of elliptical and circular orbits tended to draw extremely elliptical orbits for the former. Their drawings and descriptions showed that the planets closer to the Sun had circular orbits, while the ones further out were elliptical. A drawing by one student (Figure 2) shows a linear progression in ellipticity, with the outermost planets having the most eccentric trajectories. One other student believed that the orbits for planets were all elliptical but were circular for their moons.

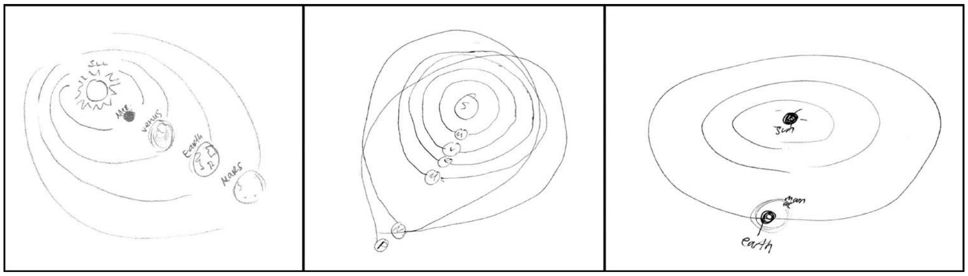

Figure 2. Examples of Solar System drawings with a mix of circular and elliptical orbits. One model shows increasing eccentricity with orbital distance from the Sun (*left*); another shows only the outermost planets as having elliptical orbits (*center*); and finally a conceptual model shows the planetary orbits as elliptical, but the moons orbit their planets in circular orbits (*right*)

4.2. Kepler's Second Law Results

Kepler's Second Law states that a planet's radius vector will sweep out equal areas over equal times. The major ramification is that the planet's speed changes throughout the orbit; the planet moves fastest at perihelion and slowest at aphelion.

Out of the total sample, only 51 students (45%) gave some response, with the rest admitting that they had no answer. Possibly because of the initial difficulty of this question, three students were given potentially leading information during their questioning by the interviewers about the speeds of planets in their orbits, and these three replies were dropped from further analysis of orbital speeds.

Out of the remainder who replied, nearly half of the students (23 or 48% of those who replied) stated that the speed was constant. A smaller number of 17 students (35% of those who replied) gave a correct or reasonably correct explanation that planets move faster when they are closer to the Sun, and slower when further away. Three of these students further mentioned the basis of their thinking: The "slingshot effect" or that the planets "slingshotted around the Sun." One student even tied the idea of a slingshot specifically to a cultural reference, the 1995 film *Apollo 13*.

Finally, a small minority of eight students (17% of the replies) gave confused answers. Three were at best able to claim that the speed of a planet changes in its orbit but could not describe how it changed or simply acknowledging that gravity played some role in the speeds. One student claimed that planets move faster when further from the Sun. Another notion that appeared was that the different speeds—due to the strength of the Sun's gravity being different at different points in the orbit—led to leap years. One student believed that the speed of the Earth in its orbit would lead to shorter and longer days.

4.3. Kepler's Third Law Results

Kepler's Third Law (the Harmonic Law) states that the period of orbit P is related to the semimajor axis a: $P^2=a^3$, with P in units of years and a in units of Astronomical Units ($1\ \text{A.U.}=1.496\times10^{11}\ \text{m}$). Therefore, an outer planet takes longer to orbit the Sun and also travels at slower speeds than an inner planet.

One student was given leading information during the questioning, and his results were not used in the analysis. Twenty-one of the students (19% of the full sample) did not address the question about how planets orbited with distance. Of the remaining students who did answer, the majority of them (60 or 66%) claimed that the speeds were different. However, 12 of them could not say anything beyond that they believed that the speeds were different. Forty-seven students did give a reasonably correct answer that inner planets moved faster, with five students explicitly mentioning that Mercury was the quickest and with one additional student saying that gravity was "harder on Mercury."

Ten students were able to make connections between the different sized orbits with different length years and lengths of trajectories of the planets. However, their answers did not include any ideas about planetary speeds. Four of the student answers simply implied that farther planets have larger orbits to traverse, compared to planets closer in to the Sun. The other six students spoke of different planets having different length years but again were not able to directly refer to speeds.

Finally, five students maintained that planetary speeds are constant, with two implying that because the orbital paths were different, the planetary years also would be different.

Eight of the students believed that planetary speed is dependent partly or wholly on the size or the mass of the planet. One student explicitly said that the smaller a planet, the faster it would move. Another commented that artificial satellites can move even faster still, presumably because of their much smaller size compared to planetary bodies. Three other students listed other factors in addition to the planet's mass, such as distance to the Sun and the mass of the Sun. For one of these three students, the list of other factors included how fast the planets rotate, how fast their moons rotate, and the influence of the gravity of Jupiter.

4.4. Central Gravitational Force in the Solar System Results

We analyzed 109 replies to question Q18 from students who did not receive leading questions from interviewers. Forty-nine (45%) of the students understood that gravity (with no mention of the Sun), or (explicitly) the Sun's gravity, or the "Sun's pull" were responsible for the motion of the planets. The student answers reflected different levels of certainty, from highly descriptive passages that show the student had studied or learned about this topic before to statements couched in doubt. Fourteen of the students (13%) also included effects other than gravity as being partially responsible for planetary motion: The mass and density of a planet, magnetic fields, number of artificial versus natural satellites in orbit around the planet, total number of moons, and total number of rings.

Eight of the students mentioned only the planet as being important for its motion, with no reference to the Sun at all. Three explicitly spoke of more massive planets as moving faster. One of these student also believed Mercury was composed primarily of metal, which made it more massive, and hence faster. The "size" or "makeup" of the planet was considerations by the other students in this category, including planetary aspects like "composition of its body" and atmosphere.

Two of the students expressed a belief that gases being expelled from the planet (like air from a balloon) cause planetary motion.

Of the remaining the students, nineteen (17%) did not know or had no answer. Seventeen replied showing that they had very confused concepts about either the question that was asked or their ideas about the answer.

5. INTERVIEW ANALYSES

5.1. Kepler's First Law Analysis

Nearly half (46%) of the students described planetary orbits as deviating from a circle (circular-ish, "not 360° symmetric"). The diagrams that they drew typically showed orbits that were oval, "egg-shaped," or slightly squashed circles. These students had a roughly correct mental model of planetary orbits in the Solar System, although the orbital shapes that they usually drew had eccentricities more similar to (if not greater than) that of Mercury and Pluto. The rather large eccentricities attributed to the planets may be associated with the common notion that the Earth's seasons are the result of its changing distance from the Sun (Baxter 1989; Atwood and Atwood 1996; Trumper 2001).

Although not technically correct, an argument can be made that the 13 students who gave only circle or circular as the answer were also roughly correct. All of the planets in the Solar System orbit via elliptical paths. However, their orbital eccentricities are relatively low: 0.244 for Pluto, 0.206 for Mercury, and <0.10 for the others. Given that face-on views of planetary orbits look very close to if not exactly circular, students would be justified in their answers if their knowledge comes from seeing diagrams of a face-on Solar System.

Nearly one-third (32%) of the respondents described orbits as elliptical or as an "ellipse." Although many agreed that the shapes were deviations from a circle (and one student had never "heard of circular orbits"), five students drew extremely elliptical orbits, many of which are almost cigar-shaped and with the Sun at the center instead of at a focus. In many instances, the interviewers asked the students from what direction the orbits were being seen from. The students confirmed that this was not a profile view, in which case a circular orbit would look highly eccentric. These students really did believe that planetary orbits were extremely elongated.

Possible sources of this mental model are the typical diagrams showing planetary orbits in the Solar System as shown from the "side" or typically 20°–45° above the ecliptic plane. In diagrams found in the vast majority of text books, magazines, television programs, and websites, the Solar System is often shown in profile, and often with the planets lined up on one side of the Sun (Figure 3). The prevalence of this type of diagram and the lack of space (or the sense of need) to show a perspective that is perpendicular to the orbital plane may introduce and help to reinforce this particular mental model of the Solar System.

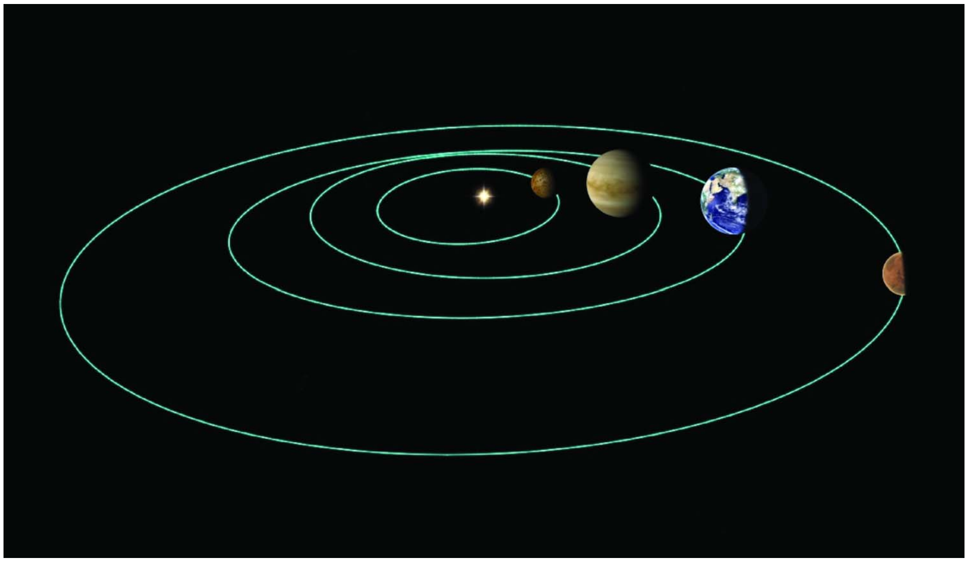

Figure 3. A common depiction of the Solar System showing it in profile. The low eccentricity orbits of the inner planets (all except for Mercury) now look highly eccentric from this perspective

The fact that Pluto has the most eccentric orbit in traditional depictions of the nine planets may be the main contributor to the last variant mental model where planetary eccentricities increase with the planet's distance from the Sun. Although Mercury has the second most eccentric orbit, it is difficult to ascertain the exact shape of its orbit in diagrams since they typically show multiple (if not all eight or nine) planets. Mercury, being the innermost, has the smallest and most easily lost orbital trajectory among all of the other planets. When planetary orbits are outlined in a figure, it will appear at first glance that the inner planets do have circular or near-circular orbits. Therefore it is not much of a stretch in the student's mind to remember that Pluto's orbit is the most eccentric, and, coupled with a common plane-on view of the inner orbits, to build a mental model where orbital eccentricities increase with distance from the Sun.

If this interpretation is correct, then those who are familiar with face-on depictions of the Solar System would include this group of students as well as those who gave circle as the answer. Thus, only one-fifth of the students (22 or 20%) had mental models that were influenced by plane-on views of the Solar System.

5.2. Kepler's Second and Third Laws Analyses

Of the students who thought that planets moved faster when they were closer to the Sun and slower when further away, *all* of them believed that the orbital shapes were elliptical or highly elliptical, a mix of circular and elliptical orbits, or otherwise not circular (oval). The students who believed the orbital shapes were circular were divided between those who gave constant speeds, gave no answer, or gave confused answers. Only seven of the 23 students describing orbital speeds as constant also described planetary orbits as circular or a mix of circles and ellipses.

Although a minority of students (17 out of 112 or 15%) knew that planetary speeds could vary within an orbit, two-fifths of the students (47 or 42%) understood that when comparing planets with different orbital distances, the closer a planet is to the Sun, the faster it would orbit. Of this group, 14 students mentioned gravity (or in one case, "stronger attraction") as the reason why closer objects orbit faster. Thus, although more students knew of noncircular orbits than circular orbits and a large fraction of students understood that planets would travel faster closer to the Sun, this correlation of distance with velocity did not transfer over to their model of how a planet might move within its own orbit, the main distinction between Kepler's Second and Third laws. Also, fewer students gave no answer when asked to compare the speeds of different planets (21) versus more students who gave no answer to the question of whether the speed of the same planet varies in its orbit (61). This suggests that the latter question brings up a concept that is so foreign that under the circumstances of the interview, the student would decline to even guess an answer.

The composition of the planet (including its atmosphere) appears in a handful of other student replies. The atmosphere is of primary importance for the two students who believe that gases expelled from the planet propel it along its orbit.

5.3. Student Ideas about Retrograde Motion

Although retrograde motion was not addressed in any of the prepared questions, two of the students mentioned the term during their interviews. One student had "just read" (presumably from the textbook) that retrograde motion was responsible for the speeds of different planets. The second student mentioned it as part of a long, confused answer about what causes the planets to move the way they do. Many of the students documented in the 1989 film *A Private Universe* incorporate retrograde motion as an inherent motion of the planet. This can lead to strange orbital shapes that are not elliptical. In Sadler's work (1992), 1% of students responded to a question on orbital shapes by picking the "figure-eight" pattern on a multiple-choice exam. We did not see any drawn or described examples of figure-eight orbital patterns in our student interviews. In addition, we did not see any drawings of epicyclic motions that could be attributed to depictions of superior planet retrograde movement as seen from the Earth. Thus, other than the two isolated examples, the students interviewed showed no evidence that depictions of retrograde motion or epicycles entered into their thinking of planetary motions.

5.4. Student Ideas about Crossing Orbits

Since a query about crossing or overlapping orbits was not among the official list of questions asked by the interviewers, we can make no definite claim about student knowledge about this topic. (However, two students told their interviewers explicitly that either planetary orbits did not cross or that she had "heard a rumor that they might cross each other, but I doubt it.") Twenty-five students (22% of the sample) had sufficient information about the structure of the Solar System, or had seen enough depictions of it, that they made drawings showing orbits crossing each other. Ten of these students could label or refer to Pluto as being the planet with an orbit that intersected another planet's orbit, while seven of this group mentioned or labeled both Pluto and Neptune. The remainder of the students merely drew noncoplanar orbits without further explanation (although one student labeled his as belonging to Earth and Mars). The drawings of three students showed more than two planets with crossing orbits (Figure 4).

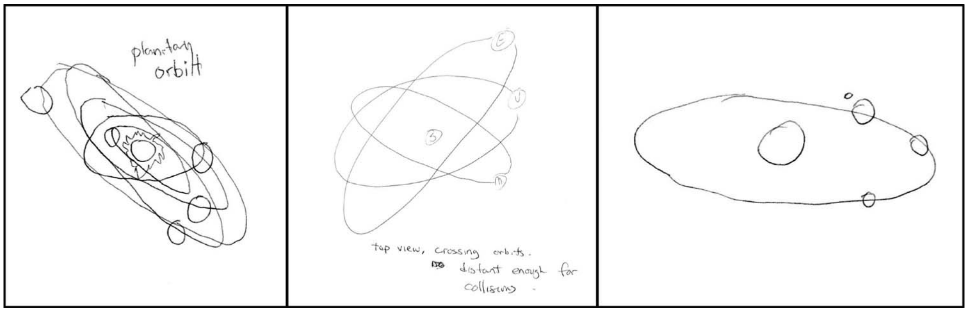

Figure 4. Solar System models where multiple planets have intersecting orbits. Although the planets on the left are roughly coplanar, the model in the center shows a wide range of inclinations. The drawing on the right shows multiple planets with orbits that completely intersect one another, i.e., they all share the same orbit

Most of the interviewers did not follow up on the student drawings that showed multiple crossing orbits or orbits with different tilts. Since we had not anticipated these results, there were no interview questions specifically addressing these models, and the interviewers tended to follow the script to cover all of the required interview topics thoroughly. The overlapping orbits might only mean that the student Solar System mental model consisted of orbits with radically different eccentricities and tilts or that the planetary orbits were highly eccentric and coplanar at the same time. The latter case would mean that planets actually could collide with one another in their intersecting orbits. No students made any statements to suggest that they thought planets would collide. (One claimed that orbits can change slightly over time but not enough for planets following them to collide with one another. Three doubted that orbits intersected, with one student explaining that otherwise, "they'd end up running into each other.")

6. THE INFLUENCE OF SOLAR SYSTEM DEPICTIONS

Our interview results confirm the finding of Sadler (1992) that the conception of a highly elliptical orbit is common among students. In one of his questions, students were asked to choose which one of the five orbital shapes presented best matched the Earth's path around the Sun. Forty-nine percent of his sample picked a circular path, with the Sun at the center of the orbit. The next most popular category chosen was a highly elongated orbit with the Sun displaced from the center. In comparison, the college-age students in our study were more than twice as likely to choose the elliptical orbit. These two results cannot be directly compared since the students taking Sadler's multiple-choice test were given four other choices to choose from, whereas the students in our study were not cued with possible answers and distractors. Yet, this common result shows the extent to which the idea of highly eccentric orbits can be so prevalent among student populations. Sadler also found that the orbital shape question had no discriminating power over how well students did overall on his test. Thus, students who knew that the Earth's orbit was closest in shape to a circle were almost equally likely to do well or poorly on the rest of the exam. On the other hand, students who picked the highly elliptical orbit distractor tended to perform better. This suggests that students who have some prior knowledge of astronomy have heard that orbits are elliptical—also suggested in our interview results—but do not understand the true extent of the eccentricity. This knowledge of orbits as elliptical coupled with the common edge-on diagrammatic depiction of the Solar System may in fact mutually reinforce the incorrect cognitive model of extremely elongated orbits.

Ojala (1997) also found textbook diagrams to be a problematic source of misconceptions in his study of students in a primary-school-teacher program. When asked to explain the cause of the seasons, the college students gave four different categories of incorrect answers that could be traced directly back to erroneous mental images that were developed after studying textbook diagrams. One of the erroneous conceptions, that a highly elliptical Earth orbit is responsible for the seasons, was found in the written responses of roughly 15% of 57 students surveyed.

Students who have no previous formal astronomy instruction are unlikely to be influenced by diagrams in astronomy textbooks. However, diagrams of the Solar System with drawn orbits of planets can be seen outside of textbooks in newspapers and magazines, on television, on websites, and in other media. Using Google's Image search tool on 6 January 2009 revealed that the term "solar system" is linked in the vast majority of the cases to depictions showing an oblique view of the planets with orbits (when drawn) that look highly elliptical. Image searches for the term "orbits" or "orbit" showed a roughly balanced mix of examples of plane-on (circular) and edge-on (elliptical) Solar System orbits. However, many depictions also show highly inclined, elliptical orbits of comets and dwarf planets mixed in with the orbits of the planets. A handful of popular pictures from the first few pages of search results show the Earth with a swarm of navigational satellites that have a mix of orbital inclinations. These latter depictions (usually of Global Positioning System or GPS satellites) may explain some of the student drawings of multiple planets sharing the same orbit, as well as orbits with wildly divergent inclinations (Figure 5). Although this is a decidedly unscientific survey of popular depictions of orbits on the World Wide Web, it hints at the possible origin of the misconception of highly elliptical planetary orbits that was held by our student interviewees.

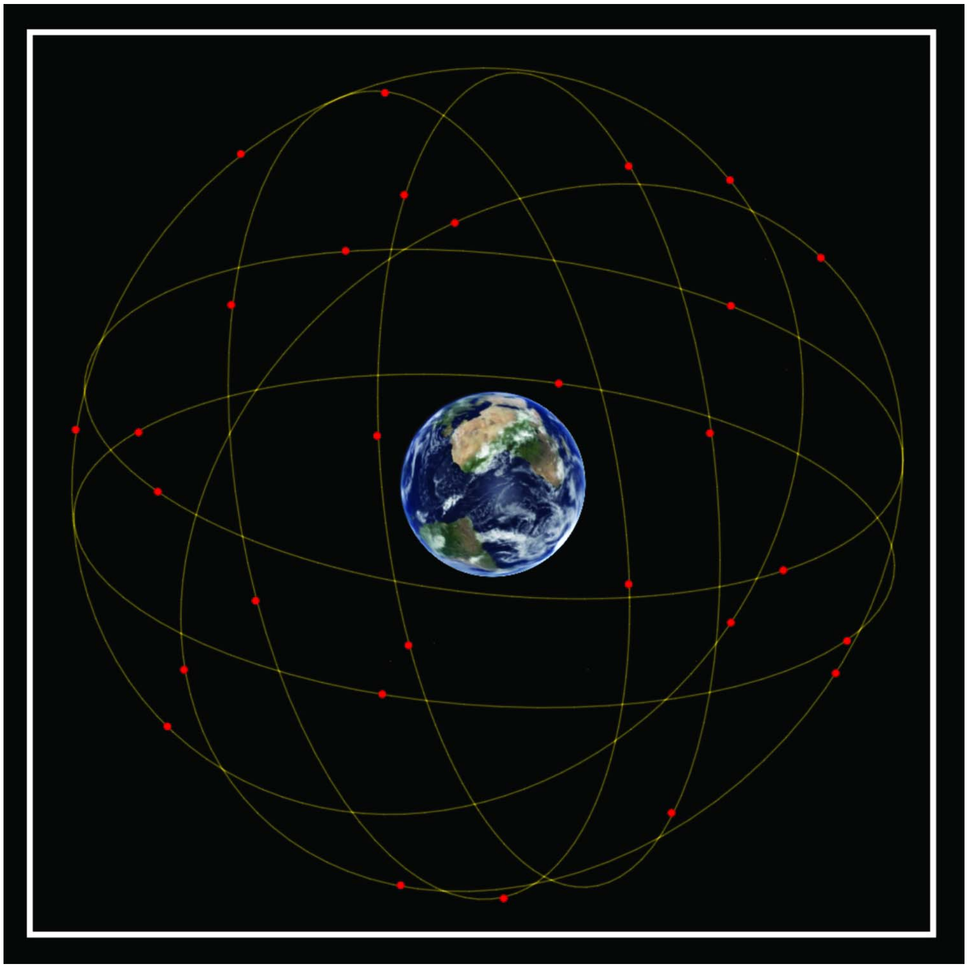

Figure 5. Diagrams like this, showing GPS satellites in orbit around the Earth, may be responsible for some of the depictions shown in Figure 4

7. SUMMARY OF RESULTS AND DISCUSSION

From interviews with 112 students starting their first week of an Astro 101 course, the most common misconception about Kepler's Laws was the belief that planetary orbits were highly eccentric. From the drawings that were made, only 12 students (11%) drew orbits that looked circular. Most students drew elongated orbits, while a few depicted both circular and elliptical orbits. Students typically had very exaggerated ideas about orbital eccentricity. The students interviewed for this study were not representative of the general population as a whole since they did sign up for an astronomy class and presumably had some interest in the topic. They may be more aware of popular portrayals of planets around the Sun, which often show an oblique view, so that circular orbits look highly eccentric. Student conceptual models with both circular and elliptical orbits often showed increasing eccentricity with planet distance from the Sun. This misconception could again be the result of encounters with popular depictions, in this case, face-on diagrams of the Solar System where Pluto's outermost orbit is prominent. Several of the students made drawings of the Solar System with multiple, overlapping, or highly inclined planetary orbits. Again, this could be the result of exposure to pictures of the Solar System in the media where the orbits of Pluto or comets are shown in addition to the planets in the ecliptic plane, or to images of the Earth surrounded by orbits of navigation satellites.

Nearly 60% of the students could not say anything about whether a planet's speed may change at different points along its orbit. Of those who answered, half believed planets orbit at a constant rate, while two-fifths gave an answer that was qualitatively correct. All students who thought that planets moved faster when closer to the Sun also expressed the belief that planetary orbits were elliptical or otherwise not circular.

Asked to compare speeds of planets in different orbits, roughly one-fifth of the students professed no opinion (a smaller fraction than those who had no answer to the previous question). Of those who did think the speeds were different, most had the qualitatively correct belief that inner planets moved faster than outer ones.

Variant models did appear in the student responses, including dependencies on the planet's mass or composition or orbital motions being the result of a rocket-like effect of gases being expelled from a planet's atmosphere.

Although nearly two-thirds of the students interviewed did not have a qualitative understanding of Kepler's Second Law, the responses from the students who did suggest a possible avenue for instruction. The following exchange is typical for the students who believed that planets closer to the Sun move faster than planets further away:

> Q: What do you know about the speeds of the planets as they orbit?
>
> A: Well, I think the speed is based on how close they are to the Sun. Because as the Sun pulls them in closer, it's, it gains a bit more speed…and when it's further away from it, it, the Sun's gravity isn't affecting it quite as much and not forcing it to move around.

Once gravity (or the "pull") of the Sun is associated with planetary motions, then the idea that the strength of this pull falls off with distance can lead to the correlation of speed with the planet's distance to the Sun as it orbits. This qualitative understanding of Kepler's Second Law also already may be present in students who have seen references in the media and pop culture to the "slingshot" effect, where a spacecraft is given a gravity assist by a larger celestial body.

These interview results suggest other specific ways that the most common student misconceptions about orbits can be addressed in the classroom. An intervention simply can consist of exposing students to a variety of views of the Solar System from different perspectives. Some textbooks show figures of the Solar System plane-on as well as from the side. Physical models with hula hoops or Solar System orreries can be used to present orbits to students from multiple perspectives. However, by their nature, such models can be used to demonstrate circular orbits but not any trajectories that deviate from circles.

A more robust approach is to use virtual simulations of astronomical phenomena using computer-generated 3D models (Barab *et al.* 2000; Yair, Mintz, and Litvak 2001; Bakas and Mikropoulos 2003; Trundle and Bell 2003; Küçüközer *et al.* 2009). A virtual environment can be used to show phenomena from any perspective within the simulation, zoomed in to show local detail, as well as pulled away to show a global context. Simulations often will give the user temporal control as well so that phenomena that vary over time can be demonstrated. Thus, not only can planetary orbital shapes be shown from multiple vantage points, but the actual motions of objects in orbit can be seen, moving forward or backward in time, sped up, or slowed down. Thus, all of Kepler's Laws can be illustrated using such visualizations.

The main objective of our ALIVE project is to study how virtual real-time simulations inside digital planetariums can be used to teach astronomy (Yu and Sahami 2007). The teaching modules developed for ALIVE were based in part on the misconceptions uncovered in our student interviews (as well as those discussed in the research literature). Therefore, to address student misconceptions about Kepler's Laws, we designed a digital planetarium experience to show: planetary orbits from multiple perspectives, the orbital motions of all of the planets through time to reveal the faster velocities of the inner planets, and the orbit of an asteroid with a highly eccentric orbit to show the variation in its orbital speed. An analysis of the preliminary results for students who received the planetarium intervention will be discussed in an upcoming paper.

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Appendix: Interview Protocols

The interview protocol was designed and the interviewers were trained in the month prior to the start of the Fall 2005 semester. The process was based in part on the Interview-about-Instances approach (Osborne and Freyberg 1985), where the goal is to get the interviewee to talk as much as possible, expressing his or her ideas in his or her own words. Thus, the interviewer always prefaced the interview with a statement that there were no right or wrong answers to the questions that she or he was about to ask; she or he was there only to learn about what the student thought about different astronomical topics. To put the more nervous student at ease, it was sometimes necessary to repeat this statement during the interview.

Interviewers also were trained to remain as neutral as possible. They were there to elicit information on what the student thought and therefore could not say, or through body language suggest, that they viewed the student response in a negative light. Interviewers, however, were asked to give the student positive encouragement, to keep him or her talking as much as possible. Since four of the eleven interviewers were astronomy instructors or had astronomy teaching experience, it was also important for them not to revert to a teaching mode. The interviewer should try not to give any verbal, gestural, or facial indications that a student response was scientifically incorrect or naive.

Questions were designed not to be leading. Simple "yes" or "no" questions were avoided. Although closed questions were used ("What object do you think is eclipsing what during a lunar eclipse?"), others were open ("Tell me what you know about planetary orbits?"). For interviewees who replied to questions with answers that did not go into very much detail, tactics were employed to have the student open up and give as much information as possible about her or his thinking. The interviewers could repeat a student statement and wait for an elaboration. Alternately, they could ask "Can you tell me more about that?" or "Why do you say that?"

The attempt to avoid leading the student seemed to be generally successful. One postinterview coding of the student answers for questions concerning Kepler's Laws revealed that four responses from three separate students (out of a total of 112) could be interpreted as being the result of leading comments by the interviewer. In all of these cases, the interviews took place in the Fall 2005 semester, when the interviewers had the least experience.

Technical terminology or jargon was minimized. For instance, instead of asking students directly about what they thought occurred during an eclipse, we began by asking them what they thought the word "eclipse" meant. If a student gave an answer suggesting reasonable knowledge about the term, the interviewer would follow-up with, "Tell me what you know about different types of astronomical eclipses." Similarly, the first question about orbits was as general as possible and did not refer to specific orbital shapes nor even imply specific physical characteristics like shapes or sizes.

The student interviews took place in a combination of empty offices and offices belonging to professors at MSCD's Department of Physics. For occupied offices, any visible display material containing astronomical information was taken down or covered up. An Apple iMac, G4 PowerPC, or G5 PowerPC was at each location, with each computer equipped with an ISIGHTS microphone and free AUDIO RECORDER 3.1 software by B. Shanfelder. The audio recording was initiated by the interviewer at the start of each interview and was automatically saved as an MP3-encoded audio file when the AUDIO RECORDER software was stopped.

The interview began with the student filling out a consent and demographic survey form. Blank sheets of paper and pencils were provided for students to make drawings as requested at multiple points in the interview. Both interview question forms and interview scoring sheets were provided to each interviewer. Although follow-up questions could not be fully anticipated and planned for, the initial question set was printed on the interview forms, and each interviewer was to read each question exactly as worded.

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