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Teaching the Scientific Method in Introductory Astronomy

by **Michael C. LoPresto**
Henry Ford Community College

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Abstract

An important goal for many instructors of introductory astronomy courses for nonscience majors is exposing students to the methods and process of science. This article describes a method for using the concepts of astronomy to demonstrate the scientific process at the beginning of an introductory astronomy course so that students will be able to use the process throughout the rest of the course.

Many instructors of astronomy believe that using astronomical concepts to teach students about the process of science is an important goal of the course. It is stated as a primary goal or theme of many introductory astronomy textbooks (Arny 2004; Comins & Kaufmann 2002; Hartmann & Impey 2002; Impey & Hartmann 2000; Kuhn & Koupelis 2002; Seeds 2004). Recent workshops on Astro 101 (see Partridge & Greenstein 2003) concluded that students should "gain the notion that the world is knowable, and that we are coming to know it through observations, experiments, and theory (the nature of progress in science)" and "an acquaintance with the history of astronomy and the evolution of scientific ideas (science as a cultural process)." The participants also recommended that "students should be exposed to the excitement of actually doing science and should receive training in the roles of observations, experiments, theory, and models ... in analyzing evidence, and in hypothesis testing."

This focus on the scientific method is appropriate because many students take introductory astronomy for general education science credits and are likely to take little (if any) additional science.

In my classes, I have found that an excellent opportunity to expose students to the scientific process usually occurs almost immediately in an introductory astronomy course. The modern picture of the solar system and its motions was developed over the centuries through a cycle of observations, interpretation, discovery of contradictions, new ideas, and improved experiments. Students can repeat much of this process in the early stages of the course, and this historical perspective builds naturally on the kinds of knowledge that students have when they enter the course.

After an introduction or overview of some sort, most texts include a chapter about the observable motions of the stars, Sun, and Moon (Arny 2004; Comins & Kaufmann 2002; Fix 2004; Fraknoi, Morrison, & Wolff 2004, Hartmann & Impey 2002; Impey & Hartmann 2000; Kuhn & Koupelis 2002; Seeds 2004). The stars, which in this early stage of a course students know (as our ancestors did) as mere points of light in the night sky, can be observed to rise, reach a maximum altitude, and then set. Further observation shows that they are moving in circles around a specific point in the sky.

This observed motion could be explained as due to either the rotation of the Earth or the rotation of the sky around a stationary Earth. Both motions can explain the observation equally well, as even Ptolemy himself explicitly stated in his treatise on the geocentric system, the *Almagest* (Crowe 1990). When asked which explanation is simpler, most students say that it is the rotating Earth. This is probably because they "know" that it is the "right" answer, but many change their votes when asked if introducing a motion that they cannot actually see or feel is simpler than saying that what they actually see is what really happens. This is a good time to introduce Occam's razor.

Lively discussions often begin when I ask students for proof that the Earth actually moves. I have rarely had a student present evidence (such as the motion of the Foucault pendulum or the Coriolis effect) that could not be explained equally well by saying that the sky is in motion. I once got the response, "prove that the Earth doesn't move," prompting me to make the point that, as is true for the accuser in a court of law, the burden of proof is on the one who proposes an idea. Often, criminal justice majors in the audience support this assertion.

The daily motion of the Sun is similar to that of the stars, but there is also a longer annual cycle of changes in midday altitude, rising and setting locations, and position among the stars. Immediate appeal to motions of the Earth for explanation, attributing the Sun's apparent motion through the stars as being due to the Earth's revolution around it, and seasonal changes in the path due to a tilt in Earth's rotational axis would forfeit an opportunity to demonstrate the scientific process. Solar motion could also be explained by revolution of the Sun around the Earth along the path that we call the ecliptic. Which is simpler here? It is not as obvious as in the case of stellar motions because a second motion and a tilt are required.

These motions are best demonstrated in a planetarium if one is available. Various planetarium software packages, almost all of which are now multiplatform, are being included with some introductory texts (Bennett et al. 2002; Comins & Kaufmann 2002; Fraknoi et al. 2004; Hartmann & Impey 2002; Impey & Hartmann 2000; Seeds 2004). There are workbooks with activities written for several of the software packages (Jordan & Peters 2002; LoPresto, *Astronomy Media* 2004; Mosley 2000; Walker 2000; Wooley 1995). To give students more control of the motions, celestial globes are useful, especially with investigations written to help them discover the motions on their own. I make more extensive use (with written activities) of celestial globes and software in the laboratory course, and have had students simulate the motions of the stars and the Sun with the globes in the lecture class. There are some excellent tutorials on these motions available for in-class use (Adams, Prather, & Slater 2003: 1-20).

Using whatever combination is available allows the instructor to minimize the amount of pure lecturing and, consistent with current trends, forces the students to be more active in their learning of the subject. It is true that students have to be somewhat passive in a planetarium, but it is still more a demonstration than a lecture.

Before moving on to the next step, which is to use the observed cycles to demonstrate the scientific process, it is very important to assess student understanding of the cycles. I have students construct a device I call a "sky wheel" to use as a tool to help them answer a series of questions about the basic observed motions of the stars and the Sun. This sky wheel is simply a two-dimensional drawing of the celestial sphere, including the ecliptic, with a transparent local horizon that can be put on top of it to show what part of the sky can be viewed from various locations on Earth (LoPresto 2002, *Cycles*: 157-162).

Student answers to these questions provide insight into how much or how little has been understood. There are several references (Crowe 1990; Davidson 1993; LoPresto 2002, *Cycles*; Rey 1980) available for students who require or desire extra exposure to this material.

Once the observed motions in the sky and possible explanations for them have been covered, students will appreciate why the geocentric system was chief among astronomical theories. Discussing its development and that of the heliocentric system (rather than immediately adopting it as the correct explanation) are both excellent ways to demonstrate the scientific process.

A class discussion led by the instructor may go as follows:

- Introduce the first observation: The sky appears to move around the Earth.
- Provide an explanation: The sky revolves around the Earth once each day.
- Point out that further observations will show that the Sun and the Moon seem to move independently of the rest of the sky. This means that the initial explanation must be revised by including the paths of the Sun and Moon.

A question to ask students here is: Which should be closer to Earth—the Sun or the Moon—and why? Some students will point out that the Moon's motion through the sky is faster, and it is therefore likely to be closer. Others will note the far more persuasive observation that the Moon covers the Sun during a solar eclipse. If the motions of the Moon are discussed right after those of the stars and the Sun and before history as in many texts (Arny 2004; Comins & Kaufmann 2002; Fix 2004; Fraknoi et al. 2004; Impey & Hartmann 2000; Seeds 2004), students should have enough knowledge of the Moon's motion and enough understanding of eclipses to devise the above responses.

The next challenge is to account for the motions of the wanderers, or "planets." These five objects look like stars (points of light) but move more like the Sun and the Moon and also need their own paths. Ask students what order the planets should be in. Some will suggest placing them according to how fast they move through the sky, just as with the Moon and the Sun. Ordering them according to brightness is often mentioned first. This is a useful example of perfectly logical reasoning leading to an unsatisfactory result, something that certainly does happen in science.

Now comes retrograde motion. The planets circle the Earth in simple direct orbits. In order to explain their periodic loop-the-loop motion, they must be placed on paths called epicycles whose centers orbit the Earth. This is a good place to insert an activity on retrograde motion and its explanation (Adams & Slater 2000).

Once explanations for all observations have been pieced together, we have what can be called a "theory." Granted, parts of this discussion are somewhat simplified and not precisely historical, but the idea that observations lead to explanations, further observations eventually lead to revised explanations, and revised explanations lead to a theory is the essence of the scientific process. I believe that it is more effective to demonstrate the scientific method by examples—such as having students participate in interactive stories of discovery—rather than just listing the steps as if they were a set of cookbook instructions.

It often surprises students that the geocentric theory was considered very successful for well over a thousand years. Discussing why it was successful is a good way to introduce some of the criteria for a successful theory. First of all, it worked. It could be used to predict the future positions of objects. Despite the complications of the planets (specifically, their retrograde motion), it was fairly simple. It appealed to common sense; people saw everything moving around the Earth, and that was what the theory proposed. Finally, the least scientific but perhaps most important historical reason for the theory's success was Earth's central position. People, and especially some religions, thought it was inevitable that the Earth be the center of the universe. This is an important indicator that science, like all disciplines, is not immune to the pressures and prejudices of society.

It is important to note that heliocentric explanations have been around as long as their geocentric counterparts. Aristarchus, a contemporary of Aristotle who proposed a spherical, nonmoving, and central Earth in the fourth century B.C., first introduced the heliocentric explanations after making observations that convinced him that the Sun was much bigger than the Earth (Crowe 1990: 27-30). Ptolemy acknowledged that these explanations were viable, but found them too complex because they involved motion of the Earth.

The reappearance of the heliocentric system in the 16th century began the Copernican Revolution. Through the trials (in some cases literally) of Copernicus, Tycho, Kepler, Galileo, and Newton came the eventual triumph of the heliocentric system. Tycho, through his years of observations of planetary positions, introduced the idea of taking large amounts of precise data over long periods of time. Kepler gave us the process of painstaking analysis of data and also took the important step of accepting conclusions based on the data, regardless of whether they agreed with what he expected or wanted them to be. Galileo was an observer and gave us experimentation. Whether or not these scientists invented these processes, they certainly showed their power—and generations of scientists have emulated them ever since.

Some activities I use with this material include:

- Using Copernicus's method for determining the relative distances between the Sun and the planets
- Charting his explanation for retrograde motion
- Diagramming stellar parallax
- Doing simple calculations and/or plotting graphs with Kepler's 3rd Law of Planetary Motion
- Diagramming competing explanations for the phases of Venus

(LoPresto 2002, *Cycles*: 171-174; Adams, Prather, & Slater 2003, *Lecture Tutorials*: 49-52, 65-66; Adams & Slater 2000: 209-214).

The first mention of the word "law" is often a good time to point out that although well-tested theories are often colloquially referred to as laws, there is no "final test" for a theory that makes it "law." Even after years of success, new evidence can overturn any theory. Geocentric astronomy is one example and foreshadows general relativity, which replaced Newton's law of gravitation. The current use of the term "law" in science is for relationships derived from observations (like Kepler's laws), with "theory" being used for the explanations of the observations (Berger, 1999). Criminal justice majors are again useful here, as they can verify the important point that this is a much different use of the word "theory" than in their field or in everyday life.

Last comes Newton's "Grand Synthesis." The main point I like to make is that by attaining equations (through mathematically based physical theories) that produce the same results for planetary motion as Kepler obtained based on Tycho's observations, Newton proved that both the theory and observations were a correct description. I then try to drive home the point that attaining the same result by theory and observations (or experiment) is the ultimate goal of the scientific process; the moment that this happens is the most profound and exciting moment that exists in science.

This helps prepare students to appreciate other examples in the course: that Maxwell's theoretical speed for electromagnetic waves matches the experimental speed of light; that Hertz's experiments, at the same time, verified the speed and nature of light; that Bohr's model of the hydrogen atom predicts wavelengths that are the same as those actually observed in the spectrum of hydrogen; or that Hubble's observation of the redshift verified Einstein's predictions (not believed at first, even by Einstein himself) of an expanding universe (LoPresto 2002, *Cycles*: 117-123).

It is also worth noting that at the time Newton sought to apply his theories mathematically, there was no form of mathematics suited to the task. Making the analogy that tools are usually invented when there is a need for them is a good way to explain why he invented calculus at that time (and any students who have taken calculus can thank Newton for all the fun they had!).

Newton's theories also provide a good opportunity to discuss the role of mathematics in science, because it is a tool for (or the language of) science. In addition to their irrational fear of it, many students mistakenly think that math is science. My favorite example is a student who was sure that because he had taken math courses up to and including one on partial differential equations, he was ready to study quantum field theory even though he had not yet taken any physics.

A good way to assess student understanding of this material is by having them construct a table in which they write down the contributions of Tycho, Kepler, Galileo, and Newton to both astronomy and science in general (LoPresto 2002, *Cycles*: 116). I also ask them to construct a flow chart (Impey & Hartman 2000: 17) that shows the process of science, and then give an example of applying the process to a situation in everyday life (LoPresto 2003, *Cycles*:75).

Most students do well with the table and show that they can at least see the difference between the big picture of science in general and its specific application to the concepts of astronomy. Application of a concept is the best way to test understanding, and not surprisingly, the hardest part of this exercise for many students is applying the scientific process in everyday life. There are always a few, however, whose examples do seem to show a real understanding, including a mechanic attempting to determine why a car is not running and a doctor making a diagnosis.

I have found that the time invested in studying the scientific process in this way pays off later in the course. If students are aware of what scientific theory is—our best explanation of a phenomenon based on the available data—they are much less likely to dismiss ideas as far-fetched or impossible to prove because nobody is or was actually there to "see" them happen. Examples include the large impact theory of the formation of the Moon, the reasons that the Uranian system is "on its side," or certain elements of stellar evolution or cosmology. An individual with an understanding of the scientific process is less likely to make the mistake of attempting to dismiss an idea by saying that it is "just a theory."

Perhaps even more importantly, if students have been successfully taught the scientific process, they can begin to actually do some scientific investigation later on in the course. There have been many inquiry-based group activities written and made available to aid in teaching many of the topics covered in introductory astronomy (Adams & Slater 2000; Adams et al. 2003; McNamara et al. 1997; Zeilik 2001). Some activities that I have used successfully include:

- Comparing compositions of Earth and Moon rocks to determine which theory of lunar origin is most viable (McNamara et al. 1997: 49)
- Classifying stellar or galaxy types (Adams & Slater 2000: 165, 185, 215)
- Determining the size of and distance to the Moon (LoPresto 2000)

In an attempt to measure whether students gained an appreciation of the scientific processes, one written question in which the students were asked to give a definition of science was added to the end of a 20-multiple-choice-question test on basic astronomical concepts. The test was given at the beginning and the end of the semester and was used as an assessment tool for several years (we have since switched to the Astronomy Diagnostic Test [ADT]). Scores on the multiple-choice questions increased from an average of just under 50% on the pretest to almost 70% on the posttest. On the pretest, only about 13% of the students defined science as a process rather than a subject. This percentage increased dramatically to 65% on the posttest.

The approach of attempting to instill an understanding of the scientific process in the nonscience student is consistent with the American Association for the Advancement of Science Benchmarks for Science Literacy (AAAS, Project 2061). After students leave our classes, they will continue to hear reports in the media about a range of scientific topics, including space exploration, nuclear energy, and genetic engineering. If an individual has a basic understanding of the scientific process, he or she is much more likely to realize that the scientific investigations described in the media usually will be more "works in progress" than well-tested and accepted theories. Perhaps this could make an individual less likely to be intimidated by or dismissive of what he or she hears, and possibly more interested in seeing the process play out.

I always tell students that if there is one thing I would like them to remember from a course I have taught, it is not *what* we know (i.e., who discovered something or how big or how far away an object is), but *how* we know what we know. Science is not a body of facts and figures, but an ongoing process of investigation and discovery (LoPresto 1999).

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