USING COMPUTER SIMULATIONS TO EXPLORE THE HISTORY OF ASTRONOMY

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Abstract

This paper provides a detailed description of a course on the Copernican Revolution that was discussed in a workshop at the 2009 ESERA conference. This course employs a novel approach to teaching the nature of science in which students work with computer simulations to visualize and explore astronomical phenomena and the theories proposed to explain these phenomena from the Ancient Greeks to Isaac Newton. The rationale for this approach is given, along with a description of the content covered in the course and the way in which computer simulations are used to actively engage students in evaluating and comparing scientific theories of planetary motion. Most of the simulations presented in the workshop are open-source Java programs that are available for free from http://facultyweb.berry.edu/ttimberlake/copernican/.

Introduction

This paper describes a course on the Copernican Revolution that was presented in a workshop at the 2009 ESERA conference. This course aims to teach students about the nature of science by engaging them in a study of the historical development of planetary astronomy. An historical approach to teaching science has been advocated at least since the time of Ernst Mach. The historical approach was strongly advocated in the United States as part of the reforms of General Education proposed by the Harvard Committee in 1945 and subsequently developed in later years (Cohen, 1952). More recently there has been an increased focus on teaching the nature of science in science courses (McComas, 2000). The historical approach to science teaching has been promoted as a particularly effective way of teaching students about the nature of science (Matthews, 1991; Matthews, 1994; McComas, 2000; Irwin, 2000). In the United States, recommendations for teaching the nature of science using historical examples are now included in national standards for science education, but so far there has been little attempt to incorporate history into science teaching in a meaningful way (Klosterman, 2009).

The Copernican Revolution course described in this paper was originally created by Paul Wallace (formerly of Berry College). The author began teaching this course in Fall 2008 and developed an extensive set of curricular materials for that purpose. In this course students gain familiarity with the basic phenomena of naked-eye astronomy and then explore the development of astronomical theories from the Ancient Greeks to Isaac Newton. Students spend the vast majority of their class time working in small groups to answer questions. The questions engage students in working with various theoretical models and ask students to evaluate the models based on how well they reproduce the phenomena as well as other criteria such as simplicity, fit with other (contemporary) theories, and aesthetic qualities. Ultimately students are asked to compare different theories to each other in order to evaluate the strengths and weaknesses possessed by each theory. Comparing and evaluating theories in this way is an essential part of learning the nature of science (Duschl, 1990). Many of the questions that students are asked require them to work with computer simulations, which help students to visualize how a given theory produces certain phenomenological predictions.

The combination of an historical approach with the active use of computer simulations by students is, perhaps, what makes this course unique. The remainder of this paper describes the rationale for the course, the scientific content of the course, the way computer simulations are used to actively engage students in the material, two major projects completed by students in this course, as well as some sample student comments about the course. In addition, a variety of resources are described for instructors and teacher educators who may be interested in using the curricular materials developed by the author. All of these materials are available for free under an open source license from the author's website (Timberlake, 2009).

Rationale for the Course

Teaching a science course for non-science majors at the undergraduate college level is in some ways an ideal situation. Students in these courses will not generally be expected to master specific content. This provides the instructor with tremendous flexibility in selecting both course content and methods of instruction. The selection of content and teaching methods can be dictated by the overall goals for the course, rather than by external factors such as preparation for later coursework or standardized examinations. Courses of this type often aim to teach students the fundamental principles of the discipline and this is certainly a laudable goal. However, another approach to this type of course is to use it as an opportunity to teach students about the nature of science (while at the same time teaching them *some* of the fundamental principles of the discipline).

Focusing on nature of science instruction seems particularly appropriate in the introductory astronomy course for non-science majors. Astronomy is a topic that students find fascinating, and yet of all the sciences it is the one that has the least impact on the day-to-day life of most humans. While a basic understanding of Darwinian evolution or the laws of thermodynamics might be critical for an informed citizen of today's technological era, knowledge of astronomy seems to be of less direct practical benefit. However, astronomy was the first of the modern sciences and as such it has the longest and richest history. Astronomy also poses some important philosophical questions about the place of humanity in the universe. Furthermore, students without any background in advanced mathematics and science can understand many important topics in the historical development of astronomy. For these reasons the introductory astronomy course seems to be the ideal venue for teaching students about the nature of science using an historical approach.

If the goal of an introductory astronomy course is to educate students about the nature of science, then this goal must be adequately reflected in both the course content and the methods of instruction used. Content should be selected so as to illustrate important aspects of the nature of science. The Copernican Revolution course was designed to illustrate the way theories are evaluated in science. The course emphasizes the role of both empirical and theoretical concerns in evaluating theories of planetary motion, as well as the simple fact that these theories are not evaluated in a vacuum but rather are compared to other theories. Students begin by examining the phenomena of naked-eye astronomy and then spend the remainder of the course studying various historical theories (such as the Ptolemaic system, the Copernican system, and Newtonian mechanics) that were proposed to explain these phenomena. Students are asked to examine how well each theory can reproduce the observed phenomena, whether or not each theory makes new predictions that are (or are not) verified, how well each theory fits with other contemporary scientific theories, and various aesthetic characteristics of each theory (simplicity, mathematical elegance, etc.).

To examine theories in this way students must not only know *what* each theory predicts, but also *how* the basic assumptions of each theory lead to those predictions. To achieve this goal students must actively work with the theories to examine what each theory predicts in a variety of circumstances. To this end the author has developed a sequence of activities in which students work with computer simulations to gain a better understanding of the theories and the phenomena they seek to explain. The next section provides a general discussion of the use of computer simulations in the Copernican Revolution course, and a later section provides more detailed information about specific simulations and how they are used in the course.

Using Computer Simulations to Teach the History of Astronomy

Several authors have recently begun to promote the use of computer simulations in teaching scientific topics (Wiemann & Perkins, 2006; Wiemann, Adams, & Perkins, 2008; Perkins et al., 2006; Christian & Esquembre 2007). In some cases computer simulations have been found to be more effective than actual laboratory experiments in teaching specific scientific content (Finkelstein et al., 2005). In this section I wish to discuss the specific advantages of using computer simulations to teach the historical development of planetary astronomy. First and foremost is that computer simulations allow students to directly observe astronomical phenomena that would be impossible or impractical for them to observe in the real world. Planetarium software like Starry Night allows students to make measurements of long-term phenomena like the sidereal period of planets and the precession of the equinoxes. Students should be given the chance to observe as many real phenomena as possible, but even in cases where observation is practical, like observing the shadow of a sundial, simulations can allow students to extend their observations beyond the practical limits imposed by real-world conditions.

Computer simulations also provide students with a way to visualize the abstract geometrical theories that were constructed to explain astronomical phenomena. This use of computer simulations is particularly powerful when combined with a historical approach to teaching science. Historical theories can be simulated on a computer regardless of whether or not those theories correctly represent real-world phenomena. Students can interact with these simulations to explore the strengths and limitations of these theories. For example, students can see how the theory of Eudoxus could account for retrograde motion of the planets but could not account for variations in brightness. Similarly, simulations make it easy to see how Ptolemy's theory could account for both effects as well as the correlations between them. Working with computer simulations can also help students to see how two theories that predict the same phenomena may be judged very differently because of non-empirical considerations such as simplicity, mathematical "harmony," and how well they fit with other accepted scientific theories. For example, computer simulations of the Copernican and Ptolemaic systems help to illustrate the mathematical harmony of the Copernican system but also clearly show that the Copernican system fails to fit with the Aristotelian physics that was accepted at the time Copernicus' work was first published.

Simulations can also help students see how two theories that make similar predictions for one set of phenomena (such as the apparent motions of Venus across the sky) may make very different predictions for a different set of phenomena (such as the phases of Venus). These differences in prediction can form the basis of a "crucial experiment" (such as Galileo's telescopic observations of Venus) that can help scientists decide which of the two theories is best, although by no means can such an experiment show us that either theory is *correct*. Finally, simulations can help students visualize the similarities between seemingly disparate phenomena. Isaac Newton, in his *The System of the World*, made an analogy between the motion of a projectile launched from a very high mountain and the motion of the Moon. Initially these two situations may seem quite different, but Newton presented a diagram in his book that clearly illustrated the similarities. A computer simulation allows students to interact with Newton's diagram to show even more effectively how a projectile launched with sufficient speed from a very tall mountain could orbit Earth.

Although computer simulations could be used to present instructor-led demonstrations to the entire class, a more effective use is to get students actively involved in using the simulations to answer questions. Students in the Copernican Revolution course spend most of their class time working in small groups to answer a series of questions provided on a printed worksheet. Most of these questions require students to interact with computer simulations. During a typical 75-minute class students will work with one or two different simulations and will answer perhaps 20-30 questions. Many of the questions are multiple-choice, but some require brief essay responses. At the end of each class students are asked to write a written reflection on that day's activity.

Several of the activities, especially in the first part of the course, focus on observing the motions of the stars and planets. For these activities students use *Starry Night*, which is commercial planetarium software that can be purchased for approximately $80 per license (Simulation Curriculum Corporation, 2009). It is possible that the activities could be completed using open source software such as *Celestia* (Celestia Development Team, 2008) or *Stellarium* (Stellarium Development Team, 2009).

Most of the other activities focus on theories of planetary motion. To help students visualize and understand these theories the author has developed several of new simulations. These simulations were created using the *Easy Java Simulations* (EJS) software program (Christian & Esquembre, 2007; Esquembre, 2009), part of the *Open Source Physics* (OSP) project (Christian, 2007; Open Source Physics, 2009). These simulations are distributed as executable Java programs (JAR files) and can be combined with curricular materials into a Launcher package using the OSP LaunchBuilder program. The simulations can be modified with the EJS program. All of these EJS simulations are released under the Gnu Public License and are available for free from the author's web page (Timberlake, 2009). The activity handouts are also available for free under the Creative Commons License from the same web page. The activities and simulations are described in more detail in the following section.

Content of the Course and the Use of Simulations

This section describes the sequence of topics covered in the course, as well as the ways in which computer simulations are used to engage students in the study of each topic. The material is organized in a generally historical sequence, although some topics are presented out of chronological order so that closely related material can be presented as a single unit.

Naked-eye Observations

The course begins with a survey of naked-eye observational astronomy. Students use Starry Night software to simulate observing the motion of the stars, Sun, Moon, and five classical planets (Mercury, Venus, Mars, Jupiter, and Saturn). Through a series of activities students examine the patterns of motion shown by the stars, discovering that stellar motions can be explained by the theory that all stars lay on the inner surface of a sphere that rotates around Earth. They measure the period of this rotation and find that the period of Sun's motion around the sky is slightly longer than that of the stars. This indicates that Sun moves relative to the stars, and students can observe that Sun follows a fixed path through the stars that takes one year to complete. Students also work with Java simulations of a gnomon, examining how the shadow of a gnomon changes throughout the day for various days of the year and various latitudes on Earth. By connecting these shadow observations with their Starry Night observations students are led to understand the Two Sphere theory of the Ancient Greeks, which assumes a stationary spherical Earth surrounded by a rotating celestial sphere upon which the stars are fixed. Students deepen their understanding of this theory by working with a physical or virtual Celestial Globe (see Figure 1).

Students also use Starry Night to observe the motion and phases of Moon, as well as the motion of the five classical planets. Many students are surprised to find that the classical planets generally drift eastward through the stars, like Sun and Moon, but occasionally turn around and move westward relative to the stars for a short time. Using Starry

Night students carry out accurate measurements of the time between successive "retrograde" motions, as well as the time for each planet to pass all the way around the celestial sphere. During their observations they note that the planets generally get brighter when they undergo retrograde motion, and also that retrograde motion is correlated to the motion of Sun. Students end the observational phase of the course by "discovering" that their zodiacal horoscope sign does not correspond to the location of Sun at the time of their birth, and by measuring the period of the precession of the equinoxes (the phenomenon that is responsible for this effect).

Whenever possible these computer-based activities are supplemented by real-world observation. Students are asked to make observations of the phase and position of Moon, as well as the length and direction of a gnomon's shadow. These observations provide direct information about the motion of Sun and Moon. Students also have an opportunity to observe the night sky for an hour or two, locating major constellations (especially those along the ecliptic and the celestial equator) and perhaps viewing a few notable objects (Moon, planets, nebulae) through a telescope.

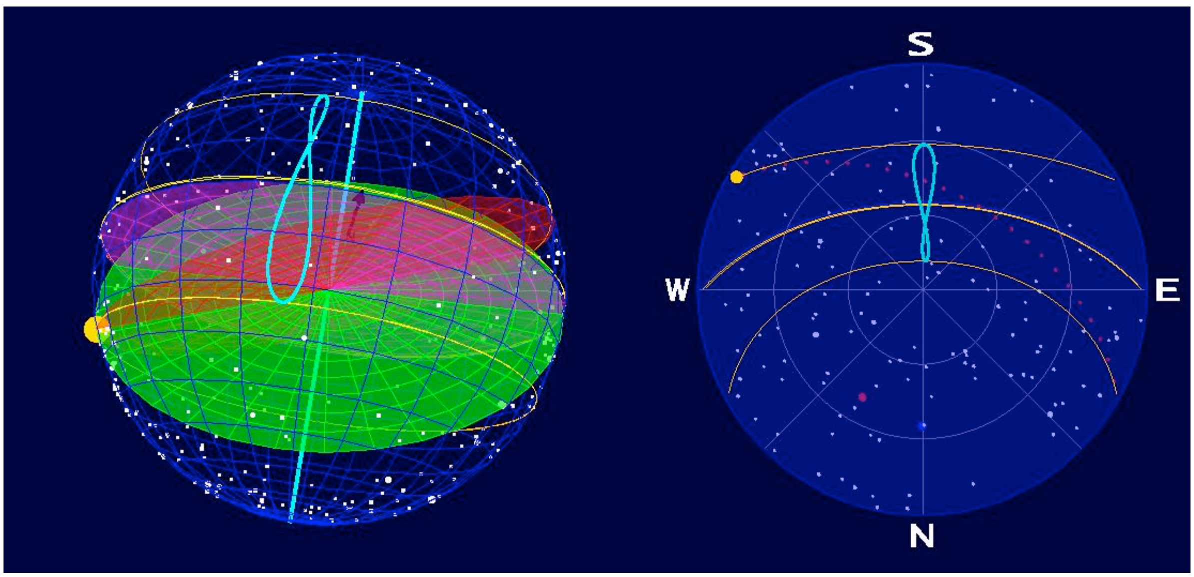

Figure 1. Screen captures from the CelestialGlobe simulation. The image on the left shows the 3D celestial globe model. The image on the right shows a 2D view of the sky as seen by an observer on Earth.

Ancient Greek Astrnomy

Students begin their study of Ancient Greek astronomical theories by returning to the Two Sphere model. They use this model to predict the motion of the stars as seen from various locations on Earth and then return to Starry Night to compare their predictions with simulated observations. Along the way they find that this powerful and simple theory accounts almost perfectly for the motion of the stars (ignoring the precession of the equinoxes). Students also reproduce Eratosthenes method for measuring the diameter of the spherical Earth.

Students then explore Aristotle's theories, beginning with his physics. By conducting a series of simple experiments students come to see the reasonableness of Aristotle's ideas. They read about Aristotle's cosmological system and work with a simulation of Eudoxus' theory of planetary motion, which was an attempt to reproduce the observed motions of the planets using Aristotle's scheme of homocentric spheres. While exploring this model students find that Eudoxus' theory can reproduce retrograde motion, but that it cannot explain the observed changes in a planet's brightness.

Although Aristotle's ideas would become dominant in the European Middle Ages, Ancient Greek astronomers deviated from some of Aristotle's views and followed a different path. Students examine the various geometrical constructions used by these later Greek astronomers such as the deferent-epicycle model of Apollonius, the eccentric circular orbit proposed by Hipparchos to model Sun's motion, and the combination of these two ideas along with a new idea (the equant) in the grand synthesis of Ptolemy. Students work with computer simulations of these various models to gain an understanding of how each model can produce different aspects of a planet's apparent motion through the stars. They find that Ptolemy's theory is able to reproduce all of the qualitative effects that they have observed in the motion of the planets, and that it provides a natural connection between brightness and retrograde motion. It does not, however, provide a natural connection between these phenomena and the motion of Sun.

The Revolutions of Copernicus

After their thorough examination of Ancient Greek astronomy students move on to examine the theory proposed in Copernicus' *De Revolutionibus*. They work with computer simulations to see how Copernicus used the rotation of Earth to produce the same effects that were previously achieved through the rotation of the celestial sphere. Similarly, they examine how the orbit of Earth about Sun can replace the motion of Sun about Earth. This leads them quite naturally to the modern explanation of the seasons. However, it also leads to the prediction of an annual parallax for the stars that had never been observed in Copernicus' day (or for a long time after). Copernicus had to explain the lack of parallax by assuming that the stars are vastly farther from Sun than Earth is.

Students then examine Copernicus' theory of the planets. Working with a simulation of the Copernican system they determine how to measure the period of a planet's orbit, noting that the procedure for measuring the period and the values obtained are quite different from what they were in the Ptolemaic system. This illustrates the fact that the meanings of scientific terms are dictated by the theory in which those terms play a role. The same term can have a very different meaning in two different theories. After measuring the periods of the planetary orbits, students determine the ordering of the planets. In the Ptolemaic system the order of the planets is somewhat arbitrary, but in the Copernican system the order of the planets is strictly dictated by observation – a point that was considered very important by Copernicus and his followers. Once the order is established students can use the same simulation and some basic trigonometry to compute the size of each planet's orbit relative to the size of Earth's orbit. This reveals a beautiful mathematical harmony between the period of each orbit and its size, another major selling point for the Copernican theory.

This exploration of the Copernican theory is followed by a class discussion in which students are asked to weigh the pros and cons of the Copernican and Ptolemaic theories. Both theories account for the phenomena equally well. The Copernican theory has some very nice mathematical features (it is more "elegant") but it is not really any simpler than the Ptolemaic theory (both theories use epicycles, etc.). However, the Copernican theory conflicted with the accepted Aristotelian physics of the time and also predicted an effect (stellar parallax) which could not be observed. This discussion is intended to help students see that Copernicus' contemporaries were behaving quite reasonably when they rejected his theory.

Tycho Brahe

One astronomer who rejected Copernicus' theory was Tycho Brahe. However, Brahe appreciated the mathematical harmonies of the Copernican system and also found flaws in the Ptolemaic system. In particular, he was unable to detect the parallax of a comet which indicated that the comet must be beyond the lunar sphere in the region that Aristotle said was perfect and unchanging. Tycho also found that the comet must pass through the spheres of the planets, proving that the planet's could not be carried by solid spheres. Using Starry Night students carry out a measurement of the parallax of Halley's Comet, following a method somewhat simpler than that used by Tycho. Students also explore Tycho's new theory of the planets in which Sun and Moon orbit Earth but the five classical planets orbit Sun (in orbits that match those of the Copernican system). By examining a simulation that compares Tychonic, Ptolemaic, and Copernican systems students gain insight into the relationships between these theories as well as a deeper understanding of the strengths and weaknesses of each theory.

Kepler's Physical Astronomy

The next portion of the course deals with the developments introduced by Johannes Kepler. Kepler's goal was to devise a physical astronomy – an astronomy that not only correctly described the motions of the heavens, but also explained why those motions, and not some other motions, occurred. Kepler's first attempt at a new astronomy was based on the idea that the five Platonic solids fit snugly between the six planetary spheres (including one for Earth). Students explore this idea using simulations that allow them to determine the ratio of spheres that inscribe and circumscribe each Platonic solid. By matching these ratios to the ratios of the planetary orbits from the Copernican theory students can judge whether or not Kepler's idea actually fits the data.

Students then move on to study Kepler's later theories of planetary motion as presented in his *Astronomia Nova* of 1609. They work with simulations that illustrate Kepler's concept of a physical force emanating from Sun that pushes each planet along in its orbit. Students examine simulations of the various orbits that Kepler tried in an attempt to precisely match the accurate observational data he had obtained from Tycho Brahe. Ultimately this struggle led Kepler to re-evaluate Copernicus' assumption that Earth moves uniformly along its orbit. Students follow Kepler's method of using Mars as a fixed beacon to map out the location of Earth in its orbit at three different times. Using a compass and straight edge they then construct an orbit for Earth and show that Earth must speed up and slow down as it moves along this orbit.

Even with his new orbit for Earth Kepler was unable to match Tycho's data. Eventually this led him to abandon the ancient assumption that all orbits must be either circular or else constructed of circular motions. Kepler tried a variety of orbits before settling on an ellipse, and students have an opportunity to explore computer simulations of some of these orbits. The sequence of theories proposed by Kepler illustrates how he used guided trial and error to zero in on the correct theory: proposing a theory, determining exactly how that theory failed, and making modifications to the theory in an attempt to compensate for these errors. This process led him to the first two of his three laws of planetary motion. Students also examine the proportional reasoning behind Kepler's third law of planetary motion.

Galileo's Telescopic Observations and Physical Theories

Galileo began observing the skies through his telescope in 1609, and in the next part of the course students use computer simulations to re-enact some of his observations. One simulation helps students reproduce Galileo's measurement of the height of a mountain on Moon, a result that directly contradicted the Aristotelian assumption that Moon was perfectly spherical. Students use another simulation to explore the sequences of phases for Venus predicted by the Copernican and Ptolemaic systems. Comparison of these predictions with Galileo's sketches of Venus clearly eliminates the Ptolemaic theory (and supports both the Copernican and Tychonic theories). Students explore Galileo's observations of, and explanation for, sunspots with another simulation and then use modern photographs of Sun to determine its rotational period. In addition, students use a simulation from the Contemporary Laboratory Experiences in Astronomy project (CLEA Staff, 2009) to observe the moons of Jupiter and show that they obey Kepler's third law of planetary motion.

Galileo became famous for his telescopic observations, but he is best known today for his discoveries in physics. Students carry out simple experiments and work with computer simulations to explore Galileo's theory of falling bodies and his idea of neutral motions (which would eventually lead to Newton's concept of inertia). A combination of these two ideas leads to Galileo's description of projectile motion, which is illustrated with another simulation. Ultimately Galileo's assault on Aristotelian physics would lead to a new synthesis of physics and astronomy at the hands of Isaac Newton.

The Newtonian Synthesis

Isaac Newton's *Philosophiae Naturalis Principia Mathematica*, published in 1687, is almost certainly the greatest scientific work ever written and the study of this work provides a grand conclusion for the course. In the *Principia* Newton lays out a small set of physical principles and then proceeds to show how these principles can account for an incredibly wide variety of phenomena on Earth and in the heavens. In particular, he shows that these principles incorporate Galileo's physics (and thus the motion of objects on Earth) as well as Kepler's laws of planetary motion (and thus the motion of objects in the heavens). Students begin their study of Newton's work by reading his three laws of motion and applying these laws to a variety of test cases. Along the way they show that inertial motion (motion at constant velocity) satisfies Kepler's second law of planetary motion. They then prove, using a geometric argument, that Kepler's second law also holds whenever an object is subject to a force that always points toward a fixed central point. This indicates that the planets may be subject to a force that always points toward Sun.

Using a computer simulation students examine Newton's explanation of circular motions as arising from an acceleration directed toward the center of the circle with a magnitude proportional to the square of the object's speed and inversely proportional to the radius of the circle. The simulation illustrates how Newton conceived of forces as acting over very small time steps and how he was able to determine the exact behavior of an object subject to continuously changing forces by letting these small time steps approach zero duration. This idea forms the basis of Newton's differential calculus. Using Kepler's third law and proportional reasoning students can guess that the force holding the planets in their orbit must have a magnitude that is inversely proportional to the square of the planet's distance from Sun. They then work with a simulation that illustrates the consequence of such a force, finding that one possible consequence is an elliptical orbit like that proposed by Kepler.

Once the existence of an inverse-square attractive force between the planets and Sun has been established, the same concept can be applied to Earth and its environs. By comparing the motion of Moon with that of a projectile launched from a tall mountain (using a simulation based on a diagram from Newton's *The System of the World*) students can see that both objects are really subject to the same inverse-square force directed toward the center of Earth. This leads directly to Newton's idea of Universal Gravitation, that all massive objects attract each other with a force that is inversely proportional to the square of the distance between them. With the complete Newtonian theory in hand students can then see that earlier results, such as Galileo's law of falling bodies and Kepler's laws of planetary motion, can now be viewed as approximations which are not strictly true in Newtonian physics.

Student Projects

In addition to their group work on the daily activities, as well as traditional assessments like homework and tests, students complete two major projects in the Copernican Revolution course. After completing their study of the Ptolemaic, Copernican, and Tychonic systems each student is given a set of observational data taken by an observer on a fictitious planet. The data describes the motions of the background stars, a sun, and two planets. Each student receives a different set of data. From this data each student must construct a Copernican system that will reproduce the observed motions. Then they must translate this Copernican system into a Ptolemaic system that will also reproduce the apparent motions. This requires a detailed understanding of how Copernicus' theory relates to specific observational data, as well as insight into the relationships between the Copernican and Ptolemaic theories.

At the end of the semester, following discussions of the Newtonian synthesis, students are asked to write a defense of the Copernican system against Aristotelian criticism. Students are given a letter from a fictitious Aristotelian astronomer in which a variety of criticisms (mostly drawn from Galileo's *Dialogue Concerning the Two Chief World Systems*) are made against the Copernican theory. Students are expected to respond to these criticisms by drawing on arguments from Galileo's telescopic observations and Newton's physics. This assignment emphasizes how the evaluation of a theory can change over time. The criticism of Copernicus' theory by his contemporaries was entirely justified given what they knew at the time, but new observations and new theoretical insights ultimately made these criticisms invalid and supported the Copernican system (as modified by Kepler and then Newton).

Student Comments

The overall student response to this course has been very positive. The overall quality of the course was rated an average of 4.61 out of 5 (5 being best) on the 39 course evaluations that were submitted over two semesters. Student comments in the course evaluations were also very positive, especially in regard to the use of computer simulations. The following is a small, but representative sample of these positive comments:

- "The course was very helpful in understanding the ways in which astronomers discovered their methods by having the class go through the same problems."
- "I appreciated the level of hands-on learning in this class. I don't think I would have learned nearly as much if it weren't experimental."
- "The simulations helped to show the different theories better than written work could sometimes."
- "The computer simulations were helpful and fun – they say much more than a picture in a book."

Not every student was pleased with the course, however. The most common criticisms were that the course covered too much information and, in a few cases, that the student would prefer to alternate activities and lectures instead of doing only activities. One student did not appreciate the basic approach of the course: "I feel that learning about ancient astronomers who came up with flawed scientific ideas does not constitute an important subject for a general education science course." Most students, however, felt that the class helped them learn how science is done.

Summary and Resources

The Copernican Revolution course described in this paper may provide an effective way to teach students about the nature of science, as well as help students gain a deep understanding of certain important topics in astronomy. The course combines three key characteristics which contribute to its effectiveness: a historical approach to the development of scientific theories, a teaching method that actively engages students in evaluating and comparing different theories, and the use of computer simulations to help students see how theories connect to observable data. This course could serve as a model for other courses that aim to teach the nature of science at the undergraduate college level or perhaps at the secondary school level. The author is currently in the process of developing another such course that will focus on the history of galactic astronomy.

Instructors and teacher educators who are interested in using all or part of the materials for this course can obtain the computer simulations and activity handouts from the author's web page (Timberlake, 2009). Those who are interested in using computer simulations to teach physics or astronomy can find a variety of high-quality materials on the web, but they are particularly encouraged to visit the Open Source Physics site (Open Source Physics, 2009). Instructors who would like to develop their own simulations, or modify the EJS simulations discussed above, should visit the Easy Java Simulations wiki page (Esquembre, 2009). Except for Starry Night (which is commercial software) all of the computer programs and other materials discussed above are available for free. Finally, Paul Wallace and the author have written a textbook for the Copernican Revolution course. Although the book is not yet ready for publication, electronic copies may be obtained by sending an email request to the author at ttimberlake@berry.edu. Any other inquiries about the course, the simulations, or the curricular materials should be sent to the same address.

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