The revolution in cosmology

While Priestley and Lavoisier developed their ideas in the realm of chemistry through experimentation, the most dramatic developments in early modern science often came from applying mathematics and philosophical principles to the physical world. Verification came later, sometimes much later when instruments were invented and methods developed that would allow an idea to be tested through observation and experiment. The prime example of this is the proposal by Nicolaus Copernicus (1473–1543), a Polish priest, lawyer, church official, painter, and astronomer, that the sun, not the earth, was the center of the universe. Copernicus became interested in astronomy and mathematics while he was a student, and put the two of them together in proposing a heliocentric system, with the earth rotating on its axis while revolving around the sun, first in an anonymous treatise and then at the very end of his life in *On the Revolutions of the Heavenly Bodies* (1543). Copernicus proposed this idea as a "mathematical hypothesis," but he clearly felt it was valid, not because he had physical proof, but because it was far simpler than Ptolemy's system in terms of the geometry involved in calculating planetary motion. This desire for simplicity, reinforced by Platonic ideas about perfect mathematical forms, meant Copernicus retained circular orbits for the planets, as the circle was the most perfect form.

Copernicus's work was discussed by astronomers, but it created no great stir, especially as it also created problems – if the earth was not the center of the universe, why did objects fall? And if it rotated, why did objects thrown into the air not land west of where they were thrown? The Aristotelian worldview was gradually challenged by others, however. From his observatory, Tycho Brahe saw and measured the appearance of a supernova and a comet in the 1570s, proving that these could not be below the moon and that the heavens did indeed change. Accepting Copernicus's idea of a heliocentric universe was too much for Brahe, however, and he posited a complicated double-centered universe, with the planets traveling around the sun, and the sun, moon, and stars revolving around a motionless earth. Using Brahe's data, Johannes Kepler proposed in 1609 that the sun was indeed the center, but that the planets moved in elliptical orbits around it at speeds that varied according to the distance the planet was from the sun. He figured out the exact proportions of speed and distance – what were later called the "laws of planetary motion" – and asserted that these applied to all the planets, including the earth. In Kepler's conceptualization, the planets circling the sun were a system distinct from the rest of the universe, clearly breaking with the Aristotelian notion of a unified cosmos, just as his elliptical orbits challenged Aristotelian (and Copernican) concepts of perfectly circular forms.

Brahe's and Kepler's observations had all been done with the naked eye, but the invention of the telescope by Dutch opticians in the early seventeenth century allowed for closer observations. On hearing about the Dutch invention, Galileo built his own telescope and used it to study the sky. Galileo was a tutor and later professor of mathematics at the universities of Pisa and Padua, where he was expected to teach courses in astronomy. Studying astronomical theory convinced him that Copernicus was right, and his telescopic discoveries offered evidence that Aristotle's understanding of the universe was wrong. The moon was not a perfectly round sphere that glowed, but was pitted like the earth and simply reflected light; the sun was not changeless, for sunspots moved across its surface. The earth was not the only center of rotation, for the planet Jupiter had *four* moons, a dramatic discovery that Galileo highlighted in *The Starry Messenger*, published in 1610. In this lively account, which the title-page describes as "unfolding great and very wonderful sights," Galileo named the moons of Jupiter the "Medicean Planets," in honor of the ruling Medici family of Florence. He wrote that this was the best possible tribute, for "all human monuments ultimately perish through the violence of the elements or by old age." Galileo's bid for patronage paid off, and Cosimo de' Medici, the Grand Duke of Tuscany, named Galileo his personal mathematician and brought him to Florence, where he continued his investigations of the heavens, and also turned his attention to the mechanics of motion on earth.

Galileo had a forceful personality and was always willing to engage in controversy. In 1615, he wrote a letter to Cosimo's mother, the Grand Duchess Christina, in which he argued that Copernican theory was consistent with biblical teachings, and in any case "the intention of the Holy Ghost is to teach us how one goes to heaven, not how heaven goes." The letter was circulated widely, a complaint was made to the Roman Inquisition, and Galileo was ordered not to

39 Letters Between Kepler and Galileo, 1597

Though published writings and scientific societies were important in spreading new ideas, people interested in science also communicated through personal letters, where they often felt freer to discuss their conclusions and theories openly. In this exchange, Kepler urges Galileo to publish his views; it would be more than a decade before Galileo took his advice.

Galileo to Kepler, August 4, 1597, Padua

I received your book, most learned sir . . . So far I have read only the introduction to your work, but I have to some extent gathered your plan from it, and I congratulate myself on the excellent good fortune of having such a man as a comrade in the pursuit of truth. For it is too bad that there are so few who seek the truth and so few who do not follow a mistaken method in philosophy . . . I have written many direct and indirect arguments for the Copernican view, but until now I have not dared to publish them, alarmed by the fate of Copernicus himself, our master. [Copernicus died peacefully in his bed; Galileo is here referring to the ridicule he mentions in the next sentence.] He has won for himself undying fame in the eyes of a few, but he has been mocked and hooted at by an infinite multitude (for so large is the number of fools).

Kepler to Galileo, October 13, 1597, Graz

I received your letter of August 4 on September 1. It gave me a twofold pleasure, first, because it sealed my friendship with you, the Italian, and second, because of the agreement in our opinions concerning Copernican cosmography . . . You advise us, by your personal example, and in discreetly veiled fashion, to retreat before the general ignorance and not to expose ourselves . . . But after a tremendous task has been begun in our time, first by Copernicus and then by many very learned mathematicians, and when the assertion that the earth moves can no longer be considered something new, would it not be much better to pull the wagon to its goal by our joint efforts, now that we have got it under way, and gradually, with powerful voices, to shout down the common herd, which really does not weigh arguments very carefully?

("Comrades in the Pursuit of Truth", trans. Mary Martin McLaughlin in James Bruce Ross and Mary Martin McLaughlin, eds., *The Portable Renaissance Reader*, pp. 597–9. Copyright 1953, renewed 1981 by Viking Penguin Inc. used by permission of Viking Penguin, a division of Penguin Group [USA] Inc.)

"hold or defend" Copernican theory, though he could "discuss it as a mathematical supposition"; this prohibition was soon extended to all authors. Galileo was chastened for a while, but in 1632 he published a long synthesis of his astronomical observations, the *Dialogue concerning the Two Chief World Systems, Ptolemaic and Copernican*. Galileo structured this as a dialogue between advocates of each system and claimed he was providing a balanced argument, but gave his inept Aristotelian the name Simplicio, and made his own position clear in the final discussion. Summoned again to Rome, Galileo was forced to recant, and was sentenced to life imprisonment; he spent the rest of his life under house arrest, though this did not stop him from publishing a further defense of new scientific ideas in many fields.

In an older view of the history of science, the trial of Galileo was part of a long battle between religion, especially Catholicism, and science, in which science, or at least Galileo, was finally vindicated in 1992 when Pope John Paul II publicly admitted the church had made a mistake in condemning him. Most historians of science today find the story to be more complicated, as Galileo had many supporters within the Catholic church, especially among Jesuits, and both personal and political issues were involved in the 1633 condemnation. Catholics and Protestants varied in their acceptance of the Copernican system and other new ideas, and it is clear that most scientists regarded their religious beliefs as essential to their scientific work.