years before Ptolemy, the physically more insightful model of Aristarchus had been proposed.

References

1 T. Heath, *Aristarchus of Samos, the Ancient Copernicus*, Clarendon Press, Oxford, UK (1913); reprinted by Dover, New York (1981).

2. Plutarch, *On the Face in the Moon's Orb*, cited in ref. 1.

3. T. Kuhn, *The Copernican Revolution: Planetary Astronomy in the Development of Western Thought*, Harvard U. Press, Cambridge, MA (1957).

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I suggest an additional myth to Mano Singham's delightful account. That is the myth that the heliocentric theory was conceived by Copernicus with no precedent. In the third century BC, Greek astronomer Aristarchus of Samos postulated the theory. He had correctly calculated the size of the Moon and its distance from Earth. He also calculated the Sun's size and its distance from Earth, but his results for the Sun were far wrong because he lacked instruments to correctly obtain an angular measurement. Nevertheless, those calculations apparently led him to the idea that Earth revolves around the Sun. Aristarchus also concluded that the fixed stars were almost infinitely far away, and he thus explained the lack of parallax in our solar circumnavigation. So he essentially had the big picture.

Copernicus mentioned Aristarchus in earlier versions of his text, but he later deleted such mention.

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The article on Copernican myths was interesting in baring the tendency of physicists to rewrite their histories, but it is clear there are other myths that even Mano Singham perpetuates. In the Ptolemaic system, the planets did not move uniformly in circles about Earth. The motion of a planet was in two circles: an epicycle on which the planet moves, and a main cycle on which the center of the epicycle moves. Although both were circles, neither centered on Earth. The main cycle was centered on a point displaced from Earth, depending on the planet. Furthermore, although the motion on the cycle was uniform, it was only so (equal angles in equal time) around the equant, a point at equal distance on the other side of the center of the circular orbit as the center is from Earth.

As Julian Barbour emphasized in his brilliant book *The Discovery of Dynamics* (Oxford University Press, 2001), these features of the main cycles are just Johannes Kepler's first two laws, to first order in the eccentricity of the ellipse. An ellipse is a circle to first order. Earth and the equant are the two foci of the ellipse, and the uniform rotation about the equant (second focus) is Kepler's second law (equal areas in equal times about the first focus) to first order. That is, the Ptolemaic system was, in many respects, closer to our modern description of the heavens than was the Copernican, which eliminated the equant and off-center circle.

Copernicus explained one great puzzle of the Ptolemaic system. The angle of the Sun around its orbit, the angle of the epicycle center around the major cycle (circular orbit) of the inner planets, and the angle of the outer planets in their epicycle were all the same at all times.

Copernicus recognized that if one scaled all the orbits appropriately, and made the Sun rather than Earth the center, then all those cycles with identical angles disappeared, leaving the planets in much simpler orbits around the Sun. That scenario also created a solar orbit for Earth around the Sun. The collapse of the number of parts of the orbits was the great advance. In achieving it, Copernicus had established a relative scale for the whole solar system.

But with that step forward, Copernicus took at least one large one backward, from our point of view. He got rid of the baggage of the offset orbit center and the equant and thereby destroyed the ellipticity of the Ptolemaic orbits. He thus had to introduce additional epicycles to explain what the Ptolemaic system explained automatically. Had he retained the equants, the Copernican system would have been simpler, with fewer epicycles than the Ptolemaic. It was 60 years before Kepler, in positing his elliptical orbits, restored and improved on the equants.

One could even argue that the centrality of Earth in the Ptolemaic system followed naturally from observation. If Earth moved, one would expect the stars, if they were bodies at different distances from Earth, to exhibit parallax. To the naked-eye accuracy of about one minute of arc, no stellar parallax is visible. Is it more sensible to postulate that the stars are at least a million times farther away than the Sun, or that Earth does not move? The latter, as emphasized by

Singham, with the dynamical laws in place at the time, seems much more sensible. Even after Isaac Newton's laws of motion and gravity made it theoretically imperative that Earth moves and not the Sun, the lack of parallax of the stars and thus the lack of any evidence that Earth moved was problematic. It took 40 years after Newton's *Principia*, with James Bradley's accidental discovery of aberration during his failure to measure any stellar parallax, to obtain the first experimental evidence—as opposed to theoretical prejudice—that Earth actually moved.

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Singham replies: If there is one thing that a study of the history of science teaches us, it is that the exact circumstances surrounding any specific scientific revolution—such as when exactly it occurred, who caused it, what factors triggered it, and how it gained acceptance—are unlikely to be answered to everyone's satisfaction. A probe through the mists of time surrounding the events enriches one's understanding of their complexity while seemingly not getting much closer to answering basic questions.

As Thomas Kuhn said,

> [Historians of science] discover that additional research makes it harder, not easier, to answer questions like: When was oxygen discovered? Who first conceived of energy conservation? Increasingly, a few of them suspect that these are simply the wrong sorts of questions to ask. . . . [A] new theory, however special its range of application, is seldom or never just an increment to what is already known. Its assimilation requires the reconstruction of prior theory and the re-evaluation of prior fact, an intrinsically revolutionary process that is seldom completed by a single man and never overnight.[1]

That is particularly true of the rich history of the Copernican revolution, even though the very accessibility of the competing models of heliocentrism and geocentrism, which can be understood by any layperson, fuels the feeling that getting at the truth of how this major change in our understanding of the solar system came about should be easy. But the truth here, like the truth elsewhere, is an elusive quantity.

The letter writers have raised important questions. Was Galileo's discovery of Jupiter's moons the decisive factor in the Copernican revolution gaining acceptance or just one of the many at play? Was the lack of acceptance of Aristarchus's earlier heliocentric model an irrational, dogma-driven mistake that set back science for more than a thousand years, or was it a perfectly rational decision by his contemporaries based on the evidence available to them at the time? How important was technology to this scientific discovery? What role does aesthetics play in the acceptance of a new idea? Although these questions have no simple answers, investigating them, as the letter writers have done, can be highly rewarding and enlightening.

I am grateful to the writers for providing additional information about the events surrounding the Copernican revolution. For every letter submitted, there are likely dozens more that could have provided additional insights. The intent of my short article was not to provide the definitive account of such a major event in scientific history—an impossible task—but to make readers aware of the richness beneath the superficial stories handed down from generation to generation and to encourage teachers and students to explore the historical record more thoughtfully. I hope the contributions of the letter writers act as further stimuli to such an endeavor.

Reference

1. T. S. Kuhn, *The Structure of Scientific Revolutions*, 3rd ed., U. Chicago Press, Chicago (1996), pp. 2, 7.

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What is 'real': A brief comparison

Steven French's review of Bernard d'Espagnat's 500-page tome *On Physics and Philosophy* (PHYSICS TODAY, June 2007, page 66) got my attention, with its repeated discussion of something d'Espagnat calls "the Real." I must confess I have not seen d'Espagnat's book, but the more I read about this Real in French's review, the more I thought I'd heard of it somewhere before. In the true scientific spirit of bringing to the attention of a researcher the results of prior research bearing on his work, I have interspersed citations from the *Summa Theologica* by Thomas Aquinas (1225–74) between passages from French's review of d'Espagnat's book.

French states that the Real "nevertheless exerts an influence on the phenomena."

Aquinas wrote, "As there can be nothing which is not created by God, so there can be nothing which is not subject to His government" (part 1, question 103, article 5).

French writes, "The grand laws of physics are 'highly distorted reflections . . . of the great structures of "the Real" ' (page 455). . . . The Real, although impossible to conceive, is nonseparable; from it, both consciousness and empirical reality 'co-emerge.' "

Aquinas wrote, "From the knowledge of sensible things the whole power of God cannot be known; nor therefore can His essence be seen. But because they are His effects and depend on their cause, we can be led from them so far as to know of God whether He exists, and to know of Him what must necessarily belong to Him, as the first cause of all things, exceeding all things caused by Him" (part 1, question 12, article 12).

Aquinas maintained that there cannot ultimately be any disagreement between faith and reason because both come from an infinitely faithful and infinitely reasonable God. It is amusing that an apparently secular philosopher such as d'Espagnat, writing for a modern audience of physicists and philosophers and basing his thought on the latest results of quantum mechanics, has nevertheless arrived at conclusions in harmony with the greatest philosopher of the Middle Ages.

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Correction

April 2008, page 32—The correct title for the painting shown by Salvador Dali is *The Persistence of Memory*. ■