Galileo, the Impact of the Telescope, and the Birth of Modern Astronomy[1]

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ONE OF THE LEADING misconceptions from the 2009 International Year of Astronomy was the idea that Galileo's brilliant telescopic observations *proved* the motion of the Earth. Allied with this myth is the parallel notion that the Catholic Church stubbornly clung to the past, refusing to accede to the obvious march of astronomical science. It is true, of course, that the Inquisition forced Galileo under the threat of torture to recant his belief in Copernicus's heliocentric system, but the efficacy of the Copernican system actually played a very small role in the trial. Galileo would have dearly loved to explain to his examiners how his observations made belief in the Copernican system more intellectually respectable even though he had no irrefutable proof of the Earth's motion, but this was an opportunity he never got.

So let us examine the status of the Sun-centered system from the pretelescopic world of Copernicus up to the age of Galileo and beyond.

Ancient astronomers had long observed that, while the planets generally move eastward against the background of stars, occasionally they stop and then move westward for a few weeks. Ptolemy modeled this so-called retrograde motion by assuming that the planets rode on secondary circles, or epicycles, which in turn traveled eastward on large carrying-circles, called deferents. The relative size of the epicycles with respect to their deferents was established by observations of the duration and arc length of the retrograde motion. Thus for Jupiter the epicycle was about a tenth as large as its deferent, Saturn's was comparatively smaller, and Mars's was huge, about two-thirds as large as its deferent. In Ptolemy's system, the mechanism for each planet was independent or, as Copernicus put it, more monster than man, with an arm from one creature, a leg from another, and a head from yet another.

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There was, however, a curious but entirely unexplained feature of the Ptolemaic system. The retrogression of Mars, Jupiter, or Saturn took place only when the planet was directly opposite in the sky from the Sun. In the Ptolemaic system this was simply an ad hoc explanation—that's how it was, with no further explanation, or, in the words of the medieval logicians, a *quia* situation, a "fact-in-itself." It was Copernicus, with his heliocentric arrangement, who turned this ad hoc explanation into a *propter quid*, or "reason why" explanation.

In his *Narratio prima* or "First Report" on the Copernican system, Georg Joachim Rheticus exclaims, "For all these phenomena appear to be linked most nobly together, as by a golden chain." It's a poetic expression, but what, in fact, can it refer to in the case of, say, Mars? Surely it is precisely this, the closely linked solar position each time Mars goes into retrogression, approximately every other year. Since the retrogression occurs when Mars is at its closest and the Earth is speeding past it, this geometry must occur when Mars is directly opposite the Sun as seen from the Earth. A glimpse at Copernicus's heliocentric arrangement shows immediately why this "opposition" configuration is essential.

While the elegance and harmony of this argument were powerful, it was not a proof of the heliocentric arrangement, particularly because throwing the Earth into a double motion, dizzily spinning on its axis and speeding in an annual motion around the Sun, seemed like nonsense. How could the Earth keep the Moon in tow as it orbited the Sun? And wouldn't people be thrown off into space from a planet spinning a dozen miles per minute? Or, as the Nuremberg astronomer Johannes Schöner argued, it would surely be harder to walk west than to walk east!

Besides these persuasive common-sense arguments, there were scriptural objections as well. Did not Psalm 104 say that the Lord God laid the foundations of the Earth that they not be moved forever? And Joshua, at the Battle of Gibeon, asked God to command the Sun, not the Earth, to stand still.

Consequently, nearly every sixteenth-century astronomer accepted Copernicus's *De revolutionibus* as an up-to-date recipe book for computing positions of planets, but definitely not as a description of physical reality. And the astronomers recognized that the heliocentric system made an observational prediction that failed. If the Earth was really orbiting the Sun, there should be tiny effects in the positions of the stars as the Earth changed its vantage point throughout the year. But this effect was not observed. Copernicus had already offered an explanation: the stars were simply too far away. "So vast, without any question, is the divine handiwork of the Almighty Creator." Eventually, in the time of Galileo, the Inquisition would censor this passage in Copernicus's book. Why cancel such a pious statement? Because Copernicus's words seemed to say that was the way God had made the Universe, and the Inquisition wanted it all to be merely hypothetical. (And eventually, but not until 1838, the minuscule annual parallax was finally detected. Copernicus was right; the stars are very far away!)

As the sixteenth century drew to a close, a few bold astronomers began to take the Copernican cosmology seriously as an actual physical description of the Universe. In England, Thomas Digges wrote in his copy of *De revolutionibus* that "the common opinion errs," and he published an English translation of the most cosmological chapter in the book, so that his countrymen "might not be altogether defrauded of so noble a part of philosophy." At Tübingen University in Germany, Michael Maestlin recoiled at the thought of the linear speeds of the distant stars if they had to spin around a fixed earth every twenty-four hours, and he taught his young student Johannes Kepler about Copernicus. Maestlin was an ambivalent Copernican, but Kepler took up the cosmology and ran with it, even suggesting that the Sun-centered arrangement was an image of the Holy Trinity.

Kepler soon prepared the first enthusiastic Copernican treatise since *De revolutionibus* itself, and in 1596 Maestlin saw it through the press in Tübingen. Kepler was proud of his little book, and sent two copies with a friend who was traveling to Italy. Both copies ended up in the hands of a young physics and mathematics teacher in Padua, Galileo Galilei, who quickly wrote a thank-you note to Kepler, indicating that he, too, held Copernican views, but privately. Kepler answered, urging Galileo to stand forth publicly with his views, but Galileo held his silence.

All this changed dramatically in 1609. At the beginning of 1608, virtually no one had a telescope. By the end of 1609 the new spyglass was ubiquitous. And what began as a carnival toy was rapidly developed into a scientific discovery machine, most notably by Galileo.

How the Telescope Changed Galileo into a Bold Copernican

Galileo received news of the Dutch invention in the spring of 1609. As soon as he learned that it consisted of a tube with a lens in each end, he was able to recreate the device. By August he was able to demonstrate an 8-power instrument to the Venetian senators, and by the end of November he had a 20-power "occhiale" or "perspicillum" (as he called it, because the word *telescope* had not yet been proposed).

In that month Galileo turned his lenses to the Moon. To his surprise and delight, he noticed little points of light in the dark part just beyond the terminator, that is, the line separating the illuminated and the dark parts of the Moon's surface. Trained as an artist with an ability to understand light and shadows, he immediately realized that these were mountain peaks just becoming illuminated by the sunlight. Throughout December 1609 he made additional watercolor drawings of the Moon, immediately recognizing that the Moon was actually earthlike, with mountains and valleys. Within a few weeks he even thought of a way to determine the heights of the lunar mountains, as great as four miles, which is only a modest exaggeration. His discovery of the earthlike nature of the Moon's surface was an immense revelation to him, because the Aristotelian vision of the heavens was that the pure, incorruptible celestial objects were totally different from the corruptible, ever-changing Earth. What he was seeing was a direct challenge to the time-honored view from antiquity.

In the following month Galileo made an even more dramatic discovery. Four previously unknown little stars in the vicinity of Jupiter turned out to be moons circling the king of the planets. Galileo, who had long yearned to leave his professorship in Padua for a position at the Medicean court in Florence, now saw a golden opportunity. He would name the moons "the Medicean stars" in the hopes of capturing Cosimo de' Medici's attention. His proposed book reporting his new discoveries would in effect become a job application, and he was in a desperate hurry to get it printed before someone else scooped him with these sensational findings. The first part of his manuscript went to the printer in Venice at the beginning of February; the final book, *Sidereus nuncius* or *Sidereal Messenger*, was ready by mid-March.

After being only a timid Copernican, Galileo was converted by his astronomical findings into a flaming Copernican. Yet he was cautious lest his enthusiasm block his chances for the appointment in Florence. Nevertheless, he allowed himself a pro-Copernican statement: "Here we have a fine and elegant argument for quieting the doubts of those who, while accepting with tranquil mind the revolutions of the planets about the sun in the Copernican system, are mightily disturbed to have the moon alone revolve about the earth and accompany it in its annual revolution about the sun." For, as he goes on to argue, the moons of Jupiter don't get lost, so why should the Earth's Moon pose a problem?

These discoveries did not, of course, *prove* the Copernican cosmology, but they provided a psychological framework for thinking about the cosmos in new terms. His discoveries and his flattering naming of the Jovian moons won him the coveted post at the Medicean court, and soon after his arrival in Tuscany he made yet another discovery, which, while it did not prove the motion of the Earth, at least disproved the traditional Ptolemaic ordering of the Universe.

There is some evidence that Galileo liked his sleep—though he occasionally stayed up past midnight, his observational log books show that he virtually never rose before dawn to make an observation. Hence he missed looking at Venus while he was in Padua, because this brightest of all planets was in the pre-dawn morning sky. But by August of 1610, when he had taken up residence in Florence, Venus had moved into the western evening sky. Galileo had every reason to believe that Venus shone by reflected light, so it should exhibit phases like the Moon. He had even demonstrated in his *Sidereal Messenger* that the Earth itself shines by reflected light, thus illuminating the Moon to produce the phenomenon known as "the old Moon in the new Moon's arms."

At first Venus showed no obvious phases, but by the beginning of December a half-moon phase was clearly visible. If Venus moved on a Ptolemaic epicycle forever *beyond* the Sun, it would move back toward a full phase, but if Venus moved *around* the Sun (as in the Copernican system), it would become a crescent phase. Galileo didn't want to lose priority for another spectacular discovery, but he would lose all credibility in the Florentine court if he gambled and lost. What to do? He concealed his hoped-for discovery in a cryptic Latin phrase, *Cynthiae figuras aemulatur mater amorum,* meaning "The mother of loves (Venus) emulates the shapes of Cynthia (the Moon)," and then he scrambled the letters, producing a double-blind anagram. He sent the anagram to Prague, where Kepler, a lover of puzzles, tried fruitlessly to crack it. For a month Galileo bided his time as Venus slowly evolved into a crescent. Ptolemy was wrong! Galileo had scored again!

But had the telescope proved the Copernican arrangement? The arrangement, yes, but not necessarily the motion of the Earth. Two decades earlier the Danish astronomer Tycho Brahe had proposed an alternative model in which the planets circled round the Sun, while the Sun itself revolved around a fixed earth. Thus the Tychonic system predicted the same Venusian phases as the Copernican system.

Meanwhile, the Grand Duchess Christina (Cosimo's mother and the power behind the Medicean throne) had posed a question for Galileo: Could the Copernican system be reconciled with Holy Scripture? For example, Joshua at the Battle of Gibeon asked the Lord to stop the Sun, not the Earth. Galileo pondered these issues, consulted writings of Saint Augustine, and composed an answer. The Bible, he said, speaks in common language so that it can be widely understood. It teaches how to go to heaven, not how the heavens go. In other words, it is neither a cosmological treatise nor a scientific textbook.

Copernican Troubles in Rome

A few years later Galileo traveled to Rome in an attempt to persuade the Catholic hierarchy to leave open unsettled cosmological questions. Alarmed conservatives reacted, annoyed because an amateur theologian was telling them how to interpret scripture when they were trying to maintain solidarity against the Protestants north of the Alps. Galileo soon learned that Copernicus's *De revolutionibus* would be prohibited "until corrected"; that is, changed in a few places to make sure readers understood that it simply described an astronomical model and not physical reality.

Cardinal Bellarmine, an Inquisitor and Rome's leading theologian, notified Galileo that he believed that Copernicus always spoke hypothetically, not positively. "For to say that assuming the earth moves and the sun stands still saves all the appearances better than eccentrics and epicycles is to speak well. This has no danger in it, and suffices for the mathematicians. But to affirm that the sun is *really* fixed in the center of the heavens and that the earth revolves around the sun is a very dangerous thing, not only by irritating the theologians and philosophers, but also by injuring our holy faith and making the sacred scriptures false. . . . To demonstrate that the appearances are saved by assuming the sun is at the center and the earth is in the heavens is not the same thing as to demonstrate that in fact the sun is in the center and the earth is in the heavens."

Clearly Bellarmine meant that just because the phases of Venus could be explained by the Copernican system, that did not mean that the Copernican system had been proved, since the Tychonic system with a fixed earth also explained the phases of Venus. Much as Galileo would have liked to find an irrefutable physical proof of the Copernican system that would have persuaded Bellarmine, he did not succeed, and Bellarmine ordered Galileo not to hold or teach the heliocentric system.

Eventually, after Bellarmine had died, and when a friend of Galileo's from Tuscany ascended the papal throne as Urban VIII, Galileo believed that he had received permission to write about cosmology. By this time Galileo was convinced that the tides provided physical evidence for the motion of the Earth, but Urban cautioned Galileo not to use *The Flux and Reflux of the Sea* (that is, the tides) as the title of his book, because that would focus too much attention on what Galileo believed was proof of the Earth's motion. "After all," Urban declared, "God in his infinite wisdom could have created the tides in many other ways, including some beyond human intellect," thus repeating what had been Bellarmine's argument earlier.

Galileo proceeded to write a brilliant dialogue (*Dialogo*) in the vernacular Italian, using the argument from the tides as a grand climax at the end, and placing Urban's words in the mouth of an Aristotelian commentator named Simplicio. There really had been a sixth-century Aristotelian philosopher named Simplicio, but Galileo's readers must surely have taken the name as a pun for "simpleton." This was not a smart move on Galileo's part, for Urban's advisers thought that placing the pope's words in the mouth of a simpleton was a direct insult. His ill-advised joke only helped to make the situation more tense when Galileo was called before the Inquisition with the charge "vehement suspicion of heresy." Ultimately Galileo was allowed to declare that he had *not* believed in the Copernican system, but he was found guilty of disobeying orders by teaching heliocentrism. His jail sentence was commuted to house arrest for the remainder of his life.

What Went Wrong?

Nearly four centuries later Pope John Paul II reopened the case, and stated that ironically Galileo had been a better theologian than those he was contending with, and he repeated the aphorism that "the Bible teaches how to go to heaven, not how the heavens go."

So, what had gone wrong back in the seventeenth century? First of all, it was not a question of a conservative Catholic Church's trying desperately to hold back the floodgates of cosmological progress. To us the Copernican system seems reasonable and uncontroversial, and we applaud Galileo for seeing this so clearly. But beggars and princes, merchants and churchmen, essentially everyone with very few exceptions, thought the idea of a spinning Earth was completely ridiculous. So in 1616 when Pope Paul V asked the Qualifiers of the Holy Office for an opinion, they already knew the answer: The motion of the Earth was obviously crazy, and they looked to the few scriptural passages that might touch on this for an answer. The eleven consultants agreed: To say that the Sun is the center of the Universe is foolish, absurd, and formally heretical, while to say the Earth moves is foolish and absurd in philosophy and erroneous in faith. Unfortunately, they were locked into a simplistic literalism and lacked the vision to entertain other cosmological possibilities. Though their opinion was not made public, it sat festering in the Vatican archives and proved toxic as the plot unfolded against the background of the Thirty Years' War and the attempt to create doctrinal solidarity against the Protestant banner of *Sola Scriptura!* (Scripture alone!).

While Galileo's *Dialogo* failed to produce the irrefutable proof he so much sought, it was nevertheless "the book that won the war." It was the account that, together with his telescopic breakthroughs, made it intellectually respectable to believe in something as counter-intuitive as a moving Earth.

But when did the proofs come? When was the "Aha! moment" when at last the Copernican system was proved?

Today basic astronomy texts present two key pieces of evidence as proof: the Foucault pendulum, which demonstrates the rotation of the Earth, and the tiny annual stellar parallax that demonstrates the revolution of the Earth around the Sun. But after Foucault swung his famous pendulum in the Pantheon in Paris in 1851, there was no dancing in the streets to celebrate the proof of the Copernican cosmology. Nor had there been joyous celebrations after stellar parallax was reported in 1838. These were too late! Everyone who mattered had long since been persuaded to believe in a moving Earth by the increasing coherence of physical ideas following Newton's *Principia* of 1687. Newton's mathematical studies of gravitation showed why people would not be spun into space by a whirling Earth. And they predicted the oblateness of the Earth caused by its spin—something that wasn't verified until the measurements by Maupertuis published in 1738. Finally, the recovery of Halley's comet in 1758 provided a popular confirmation of the *Principia* and its physics.

There simply wasn't an "Aha! moment." Science works primarily by persuasion, not by dramatic, irrefutable proofs. Confidence in the Copernican system developed slowly as evidence accumulated. Our understanding of the Universe today is founded on the openings provided by Galileo and Kepler and Newton, truly the new astronomy. It is based on plausibility and coherency. If Bellarmine could have understood that, perhaps the "Galileo Affair" would never have happened.