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Creative Revolutionaries: How Galileo and Kepler Changed the Face of Science

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Abstract

Today, as in the seventeenth century, the path to supercreativity requires unfettered access to information and new ideas, plus circumstances that provide time to think and contemplate. Galileo and Kepler were two of the supercreative heros of the early 17th century. This essay explores how they changed the face of science and the circumstances that allowed their creativity to flourish. Galileo made belief in the physical reality of heliocentrism intellectually respectable, while Kepler made physical thinking essential to the advance of astronomy.

1. Introduction

When we wish to explore the emergence of supercreativity, its impact on the development of science, and the environment that encouraged it, the names of two supercreative heros of the early 17^{th} century astronomy come quickly to mind.

Galileo and Kepler stood at the threshold of modern science. They never met though they knew of each other's work and occasionally corresponded. In many ways they were a world apart, Galileo in Catholic Italy, Kepler in Lutheran Germany. Both cultures honored astronomy and took Scripture seriously, and each astronomer/physicist wrestled with the inevitable tensions because their faith communities were wedded to an ancient Aristotelian cosmology. Yet both remained sons of their respective churches, and both approached the potential conflict between science and religion in similar ways.

Most educated people will recognize Kepler as the man who found the elliptical shape of planetary orbits. Armed with that and related insights into planetary theory, he went on to produce tables that increased the accuracy of predicted planetary positions by two orders of magnitude, a prodigious accomplishment. But to be in the league of supercreative geniuses requires, I think, more than that. He was the first to publish the theory of the telescope, something his somewhat older contemporary, Galileo, never did. In the process of working on optical theory, he proposed a new arrangement of lenses, the Keplerian telescope, which became the instrument of choice for astronomy. He described the inverted image that falls on the retina of the eye, completely reorganizing ideas of vision. Descartes remarked that "Kepler was my principal teacher in optics, and I think that he knew more about this subject than all those who preceded him."

Kepler's playful little New Year's greeting, the *Six-cornered Snowflake*, is considered a foundational treatise for mineralogy. His search for an appropriate wine after his second marriage led to an account of the volume of wine barrels that is a forerunner of integral calculus. His discussion of the supernova of 1604 was so thorough that the spectacle is still referred to as "Kepler's nova." He computed his own table of logarithms and was the first to employ logarithms in a scientific application. His analysis of the date of Christ's birth—5 B.C.—still holds. And when Henry Wotton, a diplomatic ambassador from England came to visit him in Linz, he was fascinated by a landscape that Kepler had produced, which, the astronomer declared, was drawn "non tanquam pictor, sed tanquam mathematicus"—not as an artist but as a mathematician, and he went on to explain to Wotton how he had done it with a camera obscura of his own invention.

I trust you will agree that Kepler belongs in the hall of fame for supercreativity. Yet I am going to argue that his most important influence was none of the above. But first, let me introduce another candidate for the supercreativity hall of fame, and that is of course Galileo, whose pioneering use of the telescope for astronomy we celebrated in 2009 on its 400th anniversary.

Unlike Kepler, for whom the "treadmill of calculations" was an essential component of his life, Galileo was first and foremost a hands-on inventor and experimentalist. But when he was negotiating for a job with Cosimo de' Medici, he insisted that his title be "Mathematician and Philosopher"—not only was he prepared to be a mathematician, that is, an astronomer who could handle geometrical models, but he also wanted to be credentialed as a philosopher, one who could explain how the universe was *really* made. Galileo made better and better lenses for his telescopes, ultimately converting a carnival toy into a scientific instrument. And with that instrument he could make the observations of the little stars around Jupiter, and in turn, with a brilliant leap of mental extrapolation, he could invent the satellites of Jupiter. "Wait a minute!" I can hear you saying. "He didn't *invent* the satellites of Jupiter, he *discovered* them. Columbus didn't invent America—it was there to be discovered." Maybe so, or maybe Americo Vespucci invented America.

So, I'll return briefly to this, but for now let me continue to place Galileo among the supercreative elite. Besides the satellites of Jupiter, Galileo found the craters and mountains on the moon, the multitude of faint stars that made the nebulous glow of the Milky Way, the dark and changing spots that disfigured the pure solar disk, and the phases of Venus—all of them comparatively easy initial telescopic discoveries of the solar system, though they were not easy with the relatively primitive early telescopes.

In an entirely different arena, the physics of motion, beginning with balls rolled down an inclined plane, Galileo elucidated the parabolic trajectory of a falling object and began to tease out the law of inertia. Discovering the isochrony of the pendulum, he developed the principles of the pendulum clock. Also as an inventor he conceived of the compound microscope, as well as a so-called military and geometrical compass, that is, a pair of calibrated dividers that could be used to solve a wide variety of geometrical problems.

I predicted that in 2009, officially designated by the UN as "the year of astronomy" and the 400th anniversary of Galileo's use of the telescope, you would repeatedly see the claim that with his telescope Galileo *proved* the Copernican system. The prediction was right, but the claim was wrong! Much as Galileo hoped to find an apodictic (that is, irrefutable) physical proof for the motion of the earth, he failed. As a science popularizer, he wrote the book that won the war, that is, the battle to make the heliocentric system intellectually respectable. Essentially he changed science from a logical system that worked strictly by proofs to a system of coherencies that gained credibility through persuasion. This may be his single greatest achievement, but there was something else, closely related, that also competes for the prize, namely, his brilliant campaign to overthrow the long-accepted Aristotelian cosmology and physics. So let me first take you back, not to 1632 when he wrote his *Dialogo*, the *Dialogue on the Two Chief World Systems*, but to Padua in 1609 when he first turned his newly improved telescope to the heavens, beginning the series of observations that would soon lead to his *Sidereus nuncius* or *Sidereal Messenger.*

2. Galileo's Revolutionary Observations

In the summer of 1609 Galileo had heard news of a spyglass that could bring distant objects into closer view. Learning that it was a tube with two lenses, he promptly figured out how it was done, and he set to work improving the device, making it almost literally a discovery machine. With an 8-power spyglass, the sort he was able to show to the Venetian Senate by the end of August, craters on the moon can scarcely be resolved, but by some time in October or November he had a 20-power instrument, near to the limit of the Galilean arrangement with its convex objective and concave eyepiece. With that device, resolving craters was easy, but mapping the moon was difficult on account of the restricted field of view. In any event, his early views must have convinced him that he had the makings of an illustrated astronomy book, the likes of which the world had never seen. Thus, when the new crescent moon appeared at the very end of November, he was ready with a special sheet of watercolor paper, brushes and ink.

Galileo's first attempts at recording the moon correctly showed in some detail the little detached points of light beyond the terminator (the line between the light and dark parts of the moon). His background in art and familiarity with light and shadows enabled him to understand at once that these points of light were mountain peaks catching the dawn rays of the sunlight—a profound discovery that the moon was earthlike with its heights and depths, something at great variance with the Aristotelian vision of a perfectly smooth celestial orb. Throughout that lunation and the next he added images from time to time, with improving ability.

While he was still occasionally watching the moon, early in January, he turned his "occhiale" or "perspiculum" (not yet named "telescope") to the bright planet Jupiter, which was hanging in the southeastern Paduan sky soon after sunset. His carefully dated log book, beginning with 7 January 1610, allows us to find the epoch-making moment that changed Galileo from a timid Copernican to an enthusiastic heliocentrist. On that Thursday evening he turned his telescope to the bright planet. Now this was the first time anyone had seen the *disk* of a planet, obviously a way to distinguish a planet from point-like stars, but this was not what aroused Galileo's curiosity. Perhaps he already knew that the telescope could reveal stars unseen by the naked eye, but he was surprised to observe three small stars near Jupiter itself, all in a straight line and invisible to the unaided eye. The following night, "guided by what fate he knew not" he decided to have another look. Since Jupiter was in retrograde and therefore moving west in the sky, the planet should have bypassed the stars, and they should have been left behind, to the east side of the planet. Again a surprise: this time all three were on the *west* side of the planet. How could this be? Was his memory mistaken? The next night was cloudy, but on Sunday (10 January) two of the stars were back on the east side, and the other was presumably hidden by the planet. His observation log, preserved among the Galileo papers in the National Central Library in Florence, contains perhaps the most exciting single manuscript leaf in the history of science. The following nights confirmed the arrangement of Jupiter's little stars, except that on Tuesday the third star was on the western side. And then, on Wednesday, a really big surprise! There were actually *four* of the little stars.

By this time Galileo must have been formulating a hypothesis to explain what he had been seeing: the little stars were actually four moons cycling about the planet Jupiter. What he had discovered were the four little stars that changed their positions; what he invented was the creative concept to explain their patterns. What an amazing conclusion! Many people had been objecting to the sun-centered Copernican system, because if the earth whirled around the sun each year, traveling at several miles *per second*, how could the earth keep the moon in tow? But everyone agreed that Jupiter was moving, and the royal planet seemed to have no trouble holding its retinue of satellites. Quite possibly this eureka-moment converted

Galileo from being a timid Copernican into an enthusiast [1]. When his log continues on the other side of the sheet, he has switched from Italian to Latin, then the international language of science. Clearly Galileo had something to write about for an international audience.

Undoubtedly Galileo had it in mind to publish an illustrated description of his lunar discoveries, but he seems to have been pretty relaxed about it until his Jovian findings. He had for some months been dreaming of a move from Padua to an appointment at the Florentine court of Cosimo II de' Medici, and suddenly the satellites of Jupiter gave him a naming opportunity, to call them "the Medicean Planets." By the end of January Galileo was on fire to produce a book of celestial discoveries. Basically an experimental physicist, Galileo was suddenly an astronomer of an entirely new stripe. His *Sidereal Messenger* would serve a dual purpose: on the one hand it was a job application for a position in Florence, on the other it could be his opening salvo against the time-honored Aristotelian cosmology. His Jovian moons would win him the position in Florence. Even more awesome, his lunar drawings would reveal that the moon was not pure crystalline aether, an unchanging and eternal celestial substance far removed from the mundane world of corruption and decay, but it was *earthlike.* The Aristotelian dichotomy was crumbling.

3. How Galileo Changed the Rules of Science

Galileo gave only hints of his Copernican stance in his *Sidereal Messenger.* He obviously wanted to avoid controversy in his job application. Given the job in Florence, which was tantamount to tenure, he could be bolder cosmologically. With his observations of sunspots, brilliantly portrayed in his *Istoria e dimostrazioni intorno alle macchie solari* (1612) (now written in the vernacular language, Italian) he was more forthcoming in his Copernican views, and then even more so in an unpublished essay for Cosimo's powerful mother, the Grand Duchess Christina, wherein he proposed a Biblical reconciliation with the heliocentric cosmology.

Ever since Copernicus' book had been published in 1543, the overwhelming response was to consider the treatise as a recipe book for calculating the positions of the planets, but definitely not a description of physical reality. If the earth was spinning around at a thousand miles per hour, what was to keep us from flying off into space? The mobility of the earth seemed a totally ridiculous idea. There was no physics to make sense of it. So not only was the Catholic hierarchy against it (as well as the Protestants), but also the man in the street thought the whole thing was absurd. What made it even more problematic for the churchmen was a group of Bible verses that, in a literal reading, seemed to demand a fixed earth. In particular, the Catholic Church was trying to maintain a united front against the Protestants and therefore did not want an amateur theologian like Galileo telling them how to interpret Scripture.

In 1616 Galileo journeyed to Rome, hoping to persuade the Catholic hierarchy to leave the cosmological options open lest they inadvertently back a system that was later refuted by convincing astronomical or physical observations. But conservative Roman theologians such as Roberto Bellarmine, and later, Pope Urban VIII, were convinced that irrefutable evidence could not be found, because God in his infinite wisdom could have created phenomena such as the tides in many alternative ways, and similarly for the phases of Venus (which Galileo had found late in 1610). To counter Galileo's lobbying, Bellarmine ordered Galileo neither to hold nor to teach the Copernican doctrine. Galileo, on the other hand, was convinced that alternative interpretations of those Scriptural passages were available, so he continued searching for irrefutable proofs for the motion of the earth.

Strictly speaking, Galileo never found the irrefutable proof he was looking for, though he thought he had come close with his argument from the tides in his brilliantly persuasive *Dialogo*, his cosmology book of 1632. It seemed nevertheless that Bellarmine and Urban had won because of the absence of any convincing physical proof for the earth's motion. As for the book, Urban and his allies were infuriated because Galileo thought he could tell them how to interpret Scripture and that he failed to take their argument to heart. Furthermore, Galileo had rather ill-advisedly placed the Pope's argument in the mouth of an Aristotelian commentator named Simplicio, which all the Italians knew was a pun on simpleton. Accordingly, Galileo was ordered to come to Rome to face the Inquisition. While he was eventually permitted to deny that he had actually believed the Copernican cosmology (and thus escaped the punishment of heresy), for the rest of his life he was placed under house arrest for teaching Copernicanism and for thinking that the Bible was not a final authority on matters scientific.

Nevertheless, Galileo was in fact winning the argument for the hearts and minds of thinking readers. He was essentially changing the rules of science by painting a picture, which, while lacking apodictic proofs, demonstrated a coherency of evidence that made a moving earth intellectually respectable. Part of his success came with his helping to break down the Aristotelian dichotomy between the terrestrial and celestial worlds. The philosophical sea change in which Galileo was a central player may well be his most consequential contribution to the rise of modern science—but whether changing the rules of proof in science or refashioning the Aristotelian cosmology ranks first is splendidly debatable.

4. Kepler's Campaign for a Physically Real Astronomy

Meanwhile, north of the Alps Johannes Kepler was also, well before Galileo, challenging the philosophical and astronomical status quo. Already as a graduate student at Tübingen University in the 1590s he had become enamored with the Copernican system, not just as a geometrical scheme for computing the places of planets, but as a physically real description of the universe. Undoubtedly he was impressed by the fact that the Copernican system automatically arranged the planets in the order of their periods, that is, Mercury, the fastest planet, fell closest to the sun while lethargic Saturn circled the sun in the most distant orbit. But why is this the case, Kepler wondered. In the old geocentric view, where the entire set of heavenly spheres spun around the earth in daily rotation, the source of motion came from outside the starry firmament, the sphere of stars that encompassed the entire physical universe. In Aristotle's opinion, it was the love of God that kept the entire system in its eternal motion. But in the Copernican system, the firmament was fixed, so the planetary motions came logically from the sun itself. At this point Kepler's physical reasoning began.

In the Copernican system the planets moved in circular orbits, but these circles were eccentric to the sun itself. Each planet, save for the earth, moved faster when in the part of its orbit closest to the sun. But, reasoning physically, Kepler thought the exception for the earth had to be wrong. The earth ought to behave like the other planets, which speeded up or slowed down depending on their distances from the sun. The earth ought to travel faster in January when it was nearest to the sun. In the modern idiom, Copernicus was not Copernican enough.

It was Kepler, the first astro-physicist, who decided to find out. At this time Kepler was laboring with the orbit of Mars, which had been his first assignment when he came to work in Prague as an apprentice with Tycho Brahe. Kepler eventually gained full access to the precious hoard of Tychonic observations for the recalcitrant planet Mars. But as he worked on Mars, he also worried about the physics of the earth. If the earth had a variable speed in its orbit, then the accepted eccentricity of its orbit had to be wrong by a factor of two, compared to what had been previously assumed. Kepler tried to measure seasonal differences in the apparent size of the sun, but these were too subtle to find convincingly. However, by using Tycho Brahe's extensive and wonderfully exact observations of Mars, he could triangulate to detect the position of the earth's orbit. The difference was small, but Kepler found the error in the previously assumed orbit of the earth. Then the physics worked consistently, and the earth really did travel faster in January.

Continuing his work on Mars, Kepler soon had the most accurate formula ever achieved for calculating its longitudes. But when it came time to predict the Martian latitudes, his orbit failed miserably. Neither Ptolemy nor Copernicus had been bothered by such a state of affairs—they simply used one model for longitude and another for latitude. But to Kepler as a physically oriented scientist, it seemed unreasonable to have a totally different geometrical model for the latitudes compared to the longitudes.

His preliminary orbit, on which he had worked so assiduously, was not wasted. It became part of his computing procedure. His was a long and arduous search, and eventually it led him to the elliptical form of the orbit. Of several very similar competing curves, this was the one that made physical sense to him. Later Isaac Newton sniffed that Kepler had guessed the ellipse, but that he, Newton, had proved it. But it was a brave intuitive physical guess and grasp that led to the right answer. When Newton said that he stood on the shoulders of giants, he may not have realized how much he owed to Kepler's insistence on physical causes.

It was not an easy or obvious path. His teacher and erstwhile mentor, Michael Maestlin, urged him to forget about physical causes, saying that astronomical phenomena demanded geometrical explanations. Ultimately much of Kepler's physics failed to pass the test of time. The concept of inertia was in its infancy—there Galileo was much ahead of him. But the importance of celestial physics was emblazoned on the title page of his monumental *Astronomia nova:* its subtitle read "based on causes, or celestial physics." Never had there been a book like it, showing in detail the laborious wrestling with error-infiltrated data to arrive finally at the ellipse. But above all, it was the New Astronomy, based on causes.

Eventually, near the end of his life, Kepler finished the work he had been hired to produce, the *Rudophine Tables*, named after his patron. It was a fabulous advance in the accuracy of its predictions of planetary positions, though most astronomers didn't have access to enough observations to appreciate how good it really was, and his tables were nearly driven out of the market by the simpler but much less accurate work by the Dutch astronomer Philippus Lansbergen. It took several decades before astronomers really appreciated how much better Kepler's tables were. His adjustment of the eccentricity of the earth's orbit had a very large effect, reducing the maximum errors in the prediction of Mars longitudes from around 5° to half a degree. And a second order of magnitude diminution of the errors came with the introduction of the ellipse. Two orders of magnitude improvement is always a remarkable achievement.

Unlike Galileo, who eschewed astronomical computing, Kepler was an astronomer's astronomer, a number cruncher par excellence. Galileo's *Dialogo* may well have won the cosmological war with the European intellectuals, but it was Kepler's *Epitome of Copernican Astronomy* and his *Rudolphine Tables* that won over the astronomers. Both men were supercreative geniuses who founded modern astronomy with a new cosmology and new rules.

5. Sustaining and Encouraging Supercreative Genius

In keeping with the challenge of this conference we must ask: What were the environments that sustained and encouraged these men of supercreative genius? Not everyone born with the gift of genius succeeds in standing out from the vast sea of their contemporaries. What can we see in the life-trajectories of Kepler and Galileo that enabled them to realize their special God-given talents?

As I have reflected on this question, it seems there are two essential components. One is access to information, and the other is the opportunity for contemplation, that is, time to think.

Access to information is very complex. It can come through tradition, through mentors, through libraries. In the long history of the human race, the development of language was a critical turning point. Given language and cerebral power, the human brain could exceed the storage capacity of the huge DNA library in each of our biological cells. The invention of writing was another giant leap, which means that the stored human knowledge is now far greater than the capacity of a single human brain.

Major libraries were among the crown jewels of ancient Greek culture, the library at Alexandria being only the most famous of a series of collections. In the Middle Ages monasteries and cathedrals became repositories for books. Amazingly, in 16th-century England there were only seven large libraries, where a large library is defined as having 5000 books, the number of volumes many of us now have in our own personal libraries. This number was and is made possible through the essential role of printing. Indeed, one can ask why a Copernicus and the idea of a heliocentric system arose in the 16th century rather than a century or more earlier. There were no fresh astronomical data driving the science into a new framework, so a key part of the answer must lie with the advent of printing with moveable type, since, with only a single known exception, Copernicus used printed materials as his sources for earlier observations, methods, and numerical data.

For students in the age of Galileo and Kepler, it was universities that provided the essential collections of books. Kepler was particularly lucky in this regard, because the state of Wurtemberg then provided free universal education, at least for boys. Kepler started out in German school, but was soon transferred to a Latin school. Eventually he won a ducal scholarship for the university at Tübingen. Besides books, universities provided teachers, who were also sources of mentoring and of new ideas. The astronomer Michael Maestlin introduced Kepler to the Copernican system. At some point, quite possibly through his family, Kepler obtained a copy of Copernicus' *De revolutionibus*. We know he showed it to his teacher and they discussed it, because Maestlin added a marginal note to the copy in a very critical spot for Kepler's later work. Furthermore, when Kepler wrote his first book, the *Mysterium cosmographicum*, or *Sacred Mysteries of the Cosmos*, it was Maestlin back in Tübingen who saw the book through the press, to the extent of actually setting part of the type.

Even while he was a theology student, the University Senate soon took note of Kepler, remarking that he had such an unusual mind that something special was to be expected of him. When the 22-year old Kepler was sent out to distant, provincial Graz to become an astronomy instructor, he complained that nothing in his background suggested a talent for mathematics, and in fact his worst grade was an A- in astronomy. But unusual mind or not, the University was unprepared to do more for him when the counter-reformation forces swept into Graz and Kepler faced unemployment. Kepler later said that it was Divine intervention that Tycho Brahe had arrived in Prague just as he was desperately looking for some place to go. It was perhaps Divine fate even more than Kepler realized, for he certainly would have preferred an invitation from Tübingen. But a busy professorship could well have stripped him of the other essential component for the flowering of supercreativity, time to think. Kepler's brief time with Tycho Brahe—only ten months—provided a second critical mentorship and launched him on his brilliant research career with patronage support and plenty of time to think.

Let us now turn similarly to Galileo. He must have come from a bookish family, in the sense that his musician father, Vincenzo Galilei, was a published author, having written a dialogue on ancient and modern music. Young Galileo was sent by his father to the university in Pisa to study medicine, a study increasingly unattractive to the boy. It was a professor of mathematics who had to mediate with Vincenzo to allow Galileo to concentrate on mathematics—surely a significant mentor, but hardly a Maestlin or a Tycho. Eventually at Pisa Galileo became an assistant professor (to use an anachronistic title), but he proved to be something of a troublemaker and he didn't get tenure. In search of a job, Galileo hoped to receive the position in Bologna, but it was won by a prolific astrologer, Giovanni Antonio Magini. Instead, Galileo found a professorship at Padua, and there his reputation grew.

For example, when Kepler sent a couple of copies of his first book, the *Sacred Mysteries of the Cosmos*, to Italy with a friend, who was instructed to give them to persons who might be interested, both books ended up with Galileo. Kepler had never heard of him, since Galileo had published nothing, and probably his friend hadn't heard of Galileo either. The friend, already in Padua on his way back to Germany from Rome, had suddenly realized that he had forgotten about Kepler's little books, and inquired about who might be interested in them. It was Galileo's name that emerged as a clever professor who would probably like the books. This would not be the last time Kepler heard about Galileo!

Yet it was over a decade later when Galileo's name came again to Kepler's attention, in 1610, with the appearance of the *Sidereus nuncius*. As a busy astronomy professor Galileo did not have much of a publication record, especially compared with the younger Kepler who had by then authored and printed numerous pamphlets and seven books including his magisterial *Astronomia nova*. A chief purpose of Galileo's *Sidereus nuncius* or *Sidereal Messenger* was as self-promotion for a position at the Medici court in Florence. And this succeeded brilliantly, for Galileo promptly got the job. Given the new-found time to think under the Tuscan patronage, Galileo became prolific indeed, a supercreative genius with a series of memorable texts including his *Dialogue on the Two Chief World Systems* and his *Discourse on Two New Sciences.*

Today, as in the seventeenth century, the path to supercreativity requires unfettered access to information and new ideas, plus circumstances that provide time to think and contemplate. Now, with the rise of the internet, the equivalent of a large library can be available wherever there are uncensored computers and power supplies. But will there be time to think? That is the question for the 21st century!

References

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