Heliocentrism was central to revolution in European astronomy.

We'll follow this idea to its conclusion with Galileo. But before we get there, there are two critical links between Copernicus and Galileo.

This is the story of Tycho Brahe and Johannes Kepler… and a violent math duel. [INTRO MUSIC PLAYS] There are a lot of quirky characters in the history of science. But Tycho Brahe is a true champion of quirk. Traditionally referred to as "Tycho," not by his last name, he was a Danish aristocrat, born in 1546—three years after De rev dropped and Copernicus also dropped.

Tycho was a good astronomer. But maybe a little too serious about knowledge: my dude got his nose cut off in 1566 during a sword duel with his cousin and fellow rich person Manderup Parsberg. Their beef was—wait for it—over mathematics.

You have to really love math to lose your proboscis over it. After the duel, Tycho had prosthetic noses made that he could attach to his face with wax. But whenever he got angry, he'd heat up and start sweating, and the wax would melt… and his nose would fall off. ...that's real.

In addition to an astronomer, Tycho was an alchemist and astrologer. He became so well known as a scientist that the Danish king kept trying to give him castles so he wouldn't move away. And Tycho kept turning down castles—until he got his own private research island, Hven On Hven, Tycho built two structures, Uraniborg, or the Castle of the Heavens, and Stjerneborg, or the Castle of the Stars.

Together, these castles represented the most state-of-the-art research labs of the day. Here, Tycho built a scientific empire. He had his own printing press, paper mill, alchemical equipment, and—most importantly—huge, expensive instruments and an army of staff scientists working for him.

In fact, Tycho worked with his younger sister, Sophie. Tycho and his staff produced some of the most precise naked-eye observations of the night sky ever. These were roughly twice as precise as similar observations by ancient Egyptian, Babylonian, and Greek astronomers.

Tycho's observations were not surpassed by those made with telescopes for a hundred years. Tycho believed in a geo-heliocentric cosmos. In this model, the sun orbits the earth, but the other planets revolve around the sun.

So Tycho was moving away from Aristotle and Ptolemy. And his hybrid model actually solved a bunch of the math problems astronomers were having with the Ptolemaic model… But it also placed the sun on a collision course with the planets. So, not perfect.

Even if the Tychonic model of the solar system had flaws, his observations paid off in other ways. Tycho observed and took precise measurements of the same sky all the time, noting that sometimes "stars" streaked around—these were comets. In 1572, he saw a nova stella, er, a new star, which we now call a supernova.

He noted that this new star didn't have a tail or show any stellar parallax, meaning an apparent shift in position against a background of distant objects. This meant that the new star had to be really, really, incredibly far away—a true star and not a comet. Moreover, the appearance of a new star meant that the heavens could change!

God could straight up add new stars! If you really believed your whole life that the heavens were perfect and unchanging, how hard would it be to adjust those beliefs just because you saw one new dim little pinpoint of light at night, a dot that nobody else cared about? That's just what Tycho did: one year after the supernova, in 1573, he dropped his own book: De nova stella, or On the New Star.

But after all that hard work, Tycho's life ended sadly. The old Danish king died, and his nineteen-year-old son took over. This not-super intellectual new king wanted his nobles to spend their energy on war, not science.

So he roused up opposition to Tycho's science castles, whipping up a mob to drive the patient observer into exile. Thus Tycho moved to Prague, in the Holy Roman Empire—where he died after only two years in exile, leaving behind an enormous meticulously detailed catalogue of observable stars and one very well-trained assistant… Johannes Kepler was born in 1571 near Stuttgart, Germany. His grandfather was rich, but his dad hadn't done so well, dying as a mercenary in the Netherlands.

Little Joey went to school on scholarship at a Latin school, seminary, and then the University of Tübingen. Which is still a great school today! Go, uh, 'Bingers!?

After college, Kepler taught math. Then, in 1600, Kepler so impressed Tycho that the older astronomer shared his secret data sets with him, and the two become close collaborators. Then politics happened: Kepler, a devout Lutheran, was told to convert to Catholicism or leave Prague.

Kepler—who used to call himself a "mangy dog" because he was so full of self-doubt—chose exile. When Tycho died in 1601, however, Kepler was immediately ordered to serve as the official imperial mathematician and continue Tycho's work. Politics!

Make up your mind! As imperial numbers person, Kepler mostly provided the emperor with advice about astrology. Remember that astronomy was seen as the less useful, theoretical cousin of the practical art of astrology.

But Kepler, thank goodness, kept making time for astronomy. In addition to the observing and cataloguing that he'd done with Tycho, Kepler worked on optical physics. And he observed a new supernova in 1604, in the foot of a constellation that is supposed to depict a Greek dude fighting a giant snake! (Or just holding it.

We aren't sure.) Kepler wrote his own De nova stella around 1605. But Kepler is famous thanks to the laws governing how planets move. Kepler published Astronomia nova, or A New Astronomy, in 1609.

This mind-zapper of a tome came from a decade of looking at Mars to figure out mathematical formulas that could predict its movements. Thoughtbubble, show us the Red Planet. Kepler calculated many versions of Mars's orbit using an equant point: this was an imaginary point in space that Copernicus had already figured out how to get rid of.

Using an equant, Kepler made a model of Mars's motion that almost fit Tycho's crazy-meticulous data set of years of observations. Almost. Kepler didn't just want a close model; he wanted to understand what was happening up there.

So he threw out his earlier models… and tried an elliptical or ovoid orbit with the sun in the center. And, in writing up his Mars study, he proposed the first two laws of planetary motion. The first law states that every planet has an elliptical orbit, with the sun at one of the

two foci of the ellipse, not its center.

The second law explains that, even though the speed at which a planet revolves around the sun will vary—because the planet will travel faster when it's closer to the sun—you can still figure out a constant speed for the planet, called an area speed. This is the area described by the little pizza slice shape made when you draw a line from the planet to the sun at time 1 and then again at time 2, whatever those times are, and then fill in the area between the lines. If you do this again later in the planet's trip, with the same interval between time points, you'll get a slice with the same area.

Sounds complicated, but it was important for showing that planets do actually move at non-uniform speeds—and yet we can describe these motions very precisely using the right mix of math and patient observation of the night sky! Thanks Thoughtbubble! Kepler didn't write the third law until 1619, by the way.

It explains the relationship between the distance from planets to the Sun and their orbital periods. This law was Kepler's attempt to explain the harmony of the "music of the spheres!" Alright, so that might not make the best scene in an action movie: Kepler stops using an imaginary dot to make circles move like eggs, and instead just draws a dang egg. But this represented a clear break with Aristotle and Ptolemy and a millennium of Christian thought.

And Kepler, unlike Copernicus, didn't hold back his theory for fear of ridicule by his peers or condemnation by the Church. In fact, religious ideas helped Kepler move toward a heliocentric, eccentric model: he saw the sun as a symbol of God the Father, at the center of things, moving planets faster when they came closer. So when Kepler plugged the Mars data into his new model, and the numbers worked out, he probably didn't rejoice at the triumph of secular thought over faith.

He rejoiced at a harmony of ideas: his faith, empirical data, and elegant math—all in sync! Kepler gave European astronomers a theory, backed by superb math, that explained natural phenomena better than Aristotle, Ptolemy, Oresme, Copernicus, and Tycho could. (Although Kepler built on work by all of them—science is a team sport!) But the most famous astronomer from this period gave astronomers a true research paradigm—ways to do science all day. You might know Galileo Galilei, born in 1564, as the person who dropped stuff off the side of a messed-up tower in Pisa.

If you recall episode one, though, you know that Galileo probably didn't conduct this experiment: the first published account of it dates from 1657, fifteen years after Galileo died. And Galileo worked on this theory a decade after he left Pisa. That said, he did prove the uniform rate of falling bodies.

And Galileo did lots of other amazing things for science, earning him uncontested rockstar status. We'll learn more about his overall contributions next week. Right now, let's talk star-gazing.

First, Galileo got his hands on a telescope in 1609 and refined this technology for years, which led to more and better observations of distant planets. In 1610, he dropped Sidereus Nuncius or The Starry Messenger - what a very good title for this book - which was his telescope-enabled description of the earth's moon and the "stars" orbiting Jupiter—which were its moons. His descriptions were based on literally never-before-possible observations and included accurate illustrations showing mountains on our moon.

And these were good drawings, because Galileo had been trained as a professional artist! And, according to Aristotle's cosmology, a planet could not orbit another planet other than earth. So Sidereus Nuncius represented an empirically based break with the older model.

Soon after, Galileo went on to make precise observations of Venus, Saturn, and even Neptune. Neptune was ultra-dim through the lens of his telescope, a mere thirty-times magnification compared to the naked eye. The best was yet to come.

In his Dialogue Concerning the Two Chief World Systems of 1632, Galileo explained the new astronomy of Copernicus to a wide audience. And he did this in terms of a debate within science about what counts as good evidence. That is, Galileo saw the birth of a new scientific paradigm as revolutionary!

Galileo argued publicly with geocentrists and believers in Tycho's hybrid model. Galileo argued that the tides demonstrate that the earth indeed moves, and that Copernicus's model is right. Saying that, as the Earth moves, the oceans slosh around on its surface.

He didn't get everything precisely right. Interestingly, Galileo knew about Kepler's theories but didn't seem interested in them. Unfortunately for Galileo, the Church also saw his work as revolutionary.

The Inquisition banned him from publishing any new work. But Galileo eventually found a Dutch publisher for his magnum opus, Two New Sciences. Published in 1638, it would become one of the foundational texts detailing a new scientific method… Next time—we'll dive into Galileo's thoughts about how to do science and meet two other key scientific Methodists, Francis Bacon—who was not also Shakespeare!—and René Descartes.

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