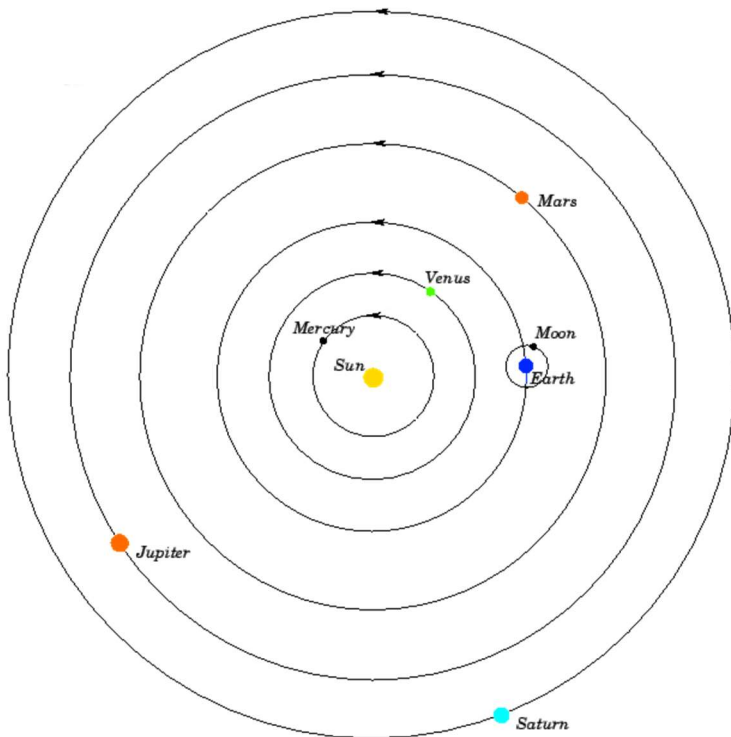


## Chapter 2: The Copernican Revolution

Copernicus, as we all know, made scientific history by proposing (in around 1514) that the sun is stationary, at the centre of the universe, and the earth orbits the sun, as do all the planets, apart from the moon. In other words, Copernicus's basic model of the universe was the one shown below (which is not drawn to scale – the outer planets actually have much larger orbits than the inner planets):



In this chapter we'll look at the arguments Copernicus used to support this model, as well as the severe difficulties it faced at the time.

## 2.1 The Elegance of the Copernican Model

The basic advantage of the Copernican (heliocentric) system was its simplicity (or elegance, economy, etc.) Thomas Kuhn refers to this as the “harmony” of the Copernican model. But what is this harmony?

One way to express this harmony is to say that, for five of the planets, Copernicus needed only one circle rather than two to describe its motion. As you can see from the diagram above, Copernicus is able to dispense with the epicycles for Mercury, Venus, Mars, Jupiter and Saturn. How then does Copernicus explain the retrograde motions of these planets?

From a Copernican perspective, the retrograde motions of the planets are an illusion, caused by the earth’s own motion. Suppose you’re driving down the highway, and overtaking a slower vehicle. In that case the slower vehicle, viewed through your side window, appears to be going backwards, but of course it isn’t really. In a similar way, the apparent retrograde motions of Mars, Jupiter and Saturn occur when the faster earth overtakes them on the ‘inside lane’.

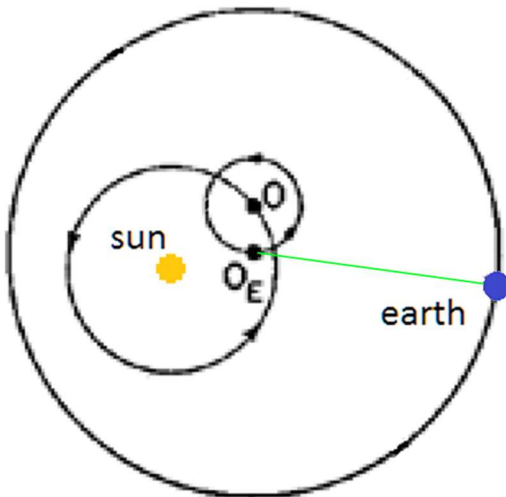
It is important to realize that, by dispensing with these epicycles, Copernicus also avoided the *ad hoc* adjustment of the epicycles referred to in Section 1.3.4. In Ptolemy’s model the solar orbit effectively appears in 6 different places in the universe, as three epicycles and two deferents are precisely synchronized to the solar orbit in both orbital period and phase. There are no such curious coincidences in the Copernican model.

Consider, in particular, the observed fact that Mercury and Venus never stray far from the sun, as viewed from earth. This fact does *not* follow from the general epicycle + deferent scheme, since it is easy to construct epicycle models where Venus and Mercury are sometimes in opposition to the sun. In order to explain this fact, Ptolemy had to

make the “ad hoc” constraint that the centre of Venus’s epicycle always lies on the straight line between the earth and the sun. In a heliocentric model, however, any planet whose orbit lies inside the earth’s orbit *must* have limited elongation – just as a matter of basic geometry. No *ad hoc* fiddling is needed to make the theory fit the data.

Let’s pause for a moment here and ask how significant this advantage is, for the Copernican model. According to Thomas Kuhn, the advantage is “largely an illusion”, although it is “a propaganda victory that the proponents of the new astronomy rarely failed to emphasize” (p. 169). Why does Kuhn say such a thing?

The reason is that the full Copernican system was (overall) just as complex and cumbersome as the Ptolemaic system. For, while Copernicus dispensed with the “major” (large) epicycles that Ptolemy used to explain retrograde motions, he required many “minor” (much smaller) epicycles to achieve a good fit between theory and data.



### The Earth’s Orbit, for Copernicus

(N.B. The diagram is not drawn to scale. In Copernicus’s model the two minor epicycles were very small in comparison to the earth-sun distance, so that the overall orbit of the earth was very nearly circular.)

The diagram above shows the full Copernican model of the earth's orbit, and gives some idea of its complexity. The earth does not simply orbit the sun. Rather, E orbits the point  $O_E$ , which orbits O, which orbits S. Thus, *three* circles are needed for each planet, not just one.

In the end, Kuhn says, both Copernicus and Ptolemy used over 30 circles, and “there was little to choose between them in economy” (Kuhn, p. 169).

At the same time, Kuhn acknowledges that the Copernican system has “aesthetic advantages” over the Ptolemaic system, since there are no unexplained coincidences between the solar orbit and other motions elsewhere. In other words, *Copernicus had an elegant explanation for the sun's special role in the universe*. Is this advantage flimsy, and mere propaganda, as Kuhn claims? Or does it have the rational force that Copernicus himself asserts?

Let us summarise the strengths and weaknesses of the Copernican system discussed so far. The strength is that Copernicus has a neat explanation for why the motions of all the planets (apart from the moon) appear to be tied to the sun's motion. The two weaknesses are that (i) the system is no more accurate in its predictions than Ptolemy's, and (ii) overall it is just as complicated as Ptolemy's model.

## 2.2 Measuring the Orbital Radii

Another advantage of the Copernican model over the Ptolemaic was that Copernicus could calculate the precise mean radius of each planet's orbit, at least as a multiple of the earth-sun distance. Recall that Ptolemy really had no idea how far away any of the planets were. Even the order of the planets was only guessed at, based on the time they each took to orbit the celestial sphere. The basic reason for this was

that each planet has both an epicycle and a deferent, which allows a lot of flexibility in constructing a model that fits the data.

Consider, for example, the observed fact that Mars's epicycles appear bigger than Jupiter's, viewed from earth, in the sense that Mars appears to backtrack further than Jupiter each time it undergoes retrograde motion. In Ptolemy's model there are two ways one can account for this fact: (i) make the two epicycles the same size, but put Jupiter further away (so that its epicycle just *looks* small) or (ii) make Jupiter's epicycle *actually* smaller than Mars's. In fact, Jupiter can be lower (closer) than Mars in such a system, as long as it moves slowly around its deferent and has a very small epicycle.

There is no such flexibility in the Copernican system, where each planet just has one circle in its orbit (ignoring the fiddly minor epicycles). The retrograde motions of Mars, Jupiter and Saturn, if you recall, are an effect (in the Copernican system) of the earth's orbit around the sun. Since Jupiter's retrograde motion is smaller than Mars's, Jupiter *must* be further away. In fact, by measuring the apparent sizes of Mars's, Jupiter's and Saturn's retrograde motions, Copernicus could calculate fairly precisely the radius of each orbit, in proportion to the earth-sun distance. (N.B. the average earth-sun distance is called one *astronomic unit*, or A.U., and is about 150 million km.) Mars's orbit was found to have a radius of 1.5 A.U., Jupiter's was 5.2 A.U., and Saturn's was 9.5 A.U. These were hard numbers, determined directly by astronomical measurements, as well as by the model itself of course.

### **2.3 Objections to the Earth's Motion**

The main objections raised against the Copernican system, in the early 17<sup>th</sup> century, concerned the claim that the earth moves. There were

three main scientific reasons, in those days, why the earth could not move:

- (i) The earth is heavy, and made of earth, so that it naturally gravitates downwards. It does not naturally move in a circle, so a huge force would be necessary to make it move that unnatural way. What force would be sufficient?
- (ii) If some enormous force were really propelling the earth around the sun, at over 100,000 km/h, then anything not nailed down would fly off.
- (iii) If the earth were really travelling around the celestial sphere then we would observe an annual stellar parallax. E.g. when the earth is close to Virgo, it should appear larger, and six months later it should appear smaller.

The first two objections are *mechanical* arguments, and will be discussed in the next chapter (on mechanics). The third objection is kinematic and will be discussed in a moment. In addition to these scientific arguments, there were also Biblical arguments, based on certain verses of the Bible that (if interpreted literally) state that the earth is stationary, and that then sun moves.

What was Copernicus's response to this third argument, from the absence of the annual stellar parallax? You can probably guess.

That there are no such phenomena for the fixed stars proves their immeasurable distance, because of which the outer sphere's [apparent] annual motion or its [parallactic] image is invisible to the eyes. For every visible object has a certain distance beyond which it can no more be seen, as is proved in optics.

In other words, there actually *is* an annual stellar parallax – it’s just that it’s too tiny to see, because the outer sphere (containing the fixed stars) is so far away from us. The earth’s orbit is a pretty big circle, of course, but compared to the outer sphere of the heavens it’s just a speck, of no size at all. In short, Copernicus said that the universe must be hundreds of times bigger than Ptolemy thought.

Copernicus’s solution seems pretty straightforward and unproblematic to us, since the vast size of the universe is something we’ve gotten used to. But in the early 17<sup>th</sup> century, the enormous gap proposed by Copernicus between the sphere of Saturn (the highest planet) and the outer sphere was pointless, bizarre, and ludicrous. Recall that Saturn’s sphere has a radius of 9.4 A.U., whereas the outer sphere would have to be around 700 times that size, i.e. something like 7,000 A.U. If one were to draw the Copernican universe to scale, on a sheet of paper, then all the planetary spheres would be invisible, compressed to an infinitesimal dot in the centre.

This vast gap in the Copernican universe, between Saturn and the fixed stars, was referred to as the “Copernican abyss”, and was considered dizzying, and wearisome to the mind. Moreover, it had the effect of making the earth seem puny by comparison, and hence unimportant. Moreover, the great astronomer Tycho Brahe argued that the Copernican universe was grotesquely out of proportion, rather like a human body in which “... a finger or a nose should surpass in size the many parts of the entire rest of the body”.

Copernicus (and other heliocentrists such as Kepler) had to argue that such an “abyss” of empty space was no big deal. Copernicus argued, for example:

The twinkling of the stars, also, shows that there is still a vast distance between the farthest of the planets, Saturn, and the Sphere of the Fixed Stars [for if the stars were very near Saturn, they should shine as he does], and it is chiefly by this indication

that they are distinguished from the planets. Further, there must necessarily be a great difference between moving and non-moving bodies. So great is this divine work of the Great and Noble Creator!

The stars twinkle, and the planets don't, which shows that they have a vast space between them. Also, the stationary objects (stars) must be properly separated from the moving parts of the universe (the planets). (Are these compelling arguments?)

Kepler pointed out that the value and significance of an entity was *not at all* a matter of its size. We human beings are, after all, just "tiny specks of dust" in terms of size, yet we are also made in the image of God. We are rational souls, and who would want to give up his soul in exchange for being as large as a mountain?

## 2.4 Giant Stars

The vast size of the stellar sphere in Copernicus's universe created another problem. Since a bright star had a measured apparent diameter of about  $1/15$  of the sun's diameter (i.e. about  $1/30$  of a degree, or 2 arc minutes) such a star ought to be about 15 A.U. away, assuming it to be about the same size as the sun. Copernicus, as we have seen, placed the stars much further away than that, at a minimum of about 7,000 A.U., which entails a *minimum* size of around 440 times the sun's diameter. In fact, even a smaller (third magnitude star) would have a minimum diameter roughly equal to that of the earth's orbit!



## The Problem with Star Sizes

The most devastating argument against the Copernican universe was the star size problem. When we look at a star in the sky, it appears to have a small, fixed width. Knowing this width and the distance to the star, simple geometry reveals how big the star is (*right*). In geocentric models of the universe, the stars lie just beyond the planets, implying that star sizes are comparable to that of the sun (*below*). But Copernicus's heliocentric theory demands that the stars be extremely far away. This in turn implies that they should be absurdly large—hundreds of times bigger than the sun (*bottom*). Copernicans could not explain away the anomalous data without appeals to divine intervention. In reality, the stars are far away, but their apparent width is an illusion, an artifact of the way light behaves as it enters a pupil or telescope—behavior that scientists would not understand for another 200 years.

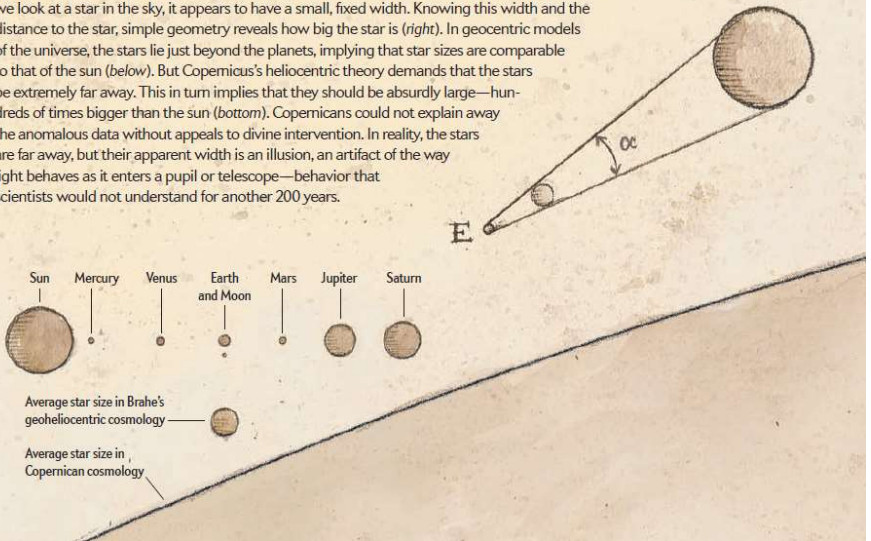


Diagram reproduced from Danielson and Graney, *Scientific American*, January 2014

Copernicus replied to this problem by saying that God, since he is an infinite being, can create stars of any size he wants. In fact, the more important an emperor is, the larger and more majestic his palace should be. So the universe, the palace of God, ought to be of unimaginable size, and contain vast stars!

Tycho replied that this argument misses the point, which is that the Copernican universe is internally *out of proportion*. Of course, the universe can be any size God wants it to be, but nature ought to have proportion and balance within itself. The Copernican universe, with its ridiculous disproportions, is therefore absurd.

## 2.5 Enter Galileo, and his telescope

Faced with these serious objections, the Copernican hypothesis rather languished between 1543 (when Copernicus published his great work, *De Revolutionibus Orbium Coelestium*) and the early 17<sup>th</sup> century. Many astronomers used Copernicus's system, but under the assumption that the earth's motion was a mathematical fiction rather than physically real. No books supporting the Copernican view were published during this time, although a few astronomers quietly held a heliocentric view.

Big things started to happen in astronomy, however, around 1609-10. In 1609 Johannes Kepler, a renowned mathematician and astronomer, published *Astronomia Nova* (New Astronomy) – a work that argued strongly for heliocentrism, while also solving many of its mathematical difficulties. In the same year Galileo (1564 – 1642) heard about the recent invention of the telescope and made his own, improved version (with greater magnification). Galileo pointed his first telescope at the heavens, and obtained new data that would cause great difficulties for Ptolemy's model of the universe. Galileo's early observations with his telescope were published in 1610, in a short book titled *Starry Messenger*.

Galileo was also a Copernican, having accepted the heliocentric view as a fairly young man, certainly by the age of 33 (i.e. in 1597) when he wrote to Kepler:

...Like you, I accepted the Copernican position several years ago and discovered from thence the causes of many natural effects which are doubtless inexplicable by the current theories. I have written up many of my reasons and refutations on the subject, but I have not dared until now to bring them into the open, being warned by the fortunes of Copernicus himself, our master, who procured immortal fame among a few but stepped down among the great crowd (for the foolish are numerous), only to be derided and

dishonoured. I would dare publish my thoughts if there were many like you; but, since there are not, I shall forebear....

You'll see that Galileo was reluctant at this time to publish his work in support of Copernicus, fearing that he (like Copernicus) might be "derided and dishonoured". It is no different today, as scientists who propose ideas that lie far outside the mainstream "orthodoxy" generally pay the price of a reduced reputation and career prospects. In his reply Kepler said, "Be of good cheer, Galileo, and come out publicly." Kepler got his wish. In Galileo's *The Starry Messenger* (1610) which described his early observations using a telescope, he included (right at the end) a brief argument for the Copernican view.

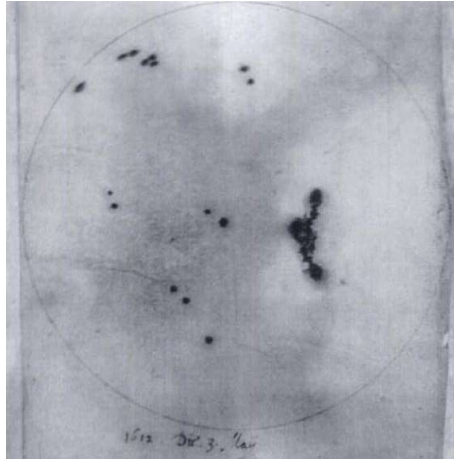
After this tentative beginning, Galileo gradually became the most aggressive champion of the Copernican heliocentric model, which he was absolutely determined to prove. He argued for it theologically, showing that it was not really in conflict with Holy Scripture. Most famously, in 1632 he wrote a lengthy treatise supporting the Copernican view, titled *Dialogue Concerning the Two Chief World Systems*. (That book got him into trouble, but more about that later.)

First we should discuss what Galileo saw with his telescope, and why it contradicted the universe of Aristotle and Ptolemy. There were 3 such observations:

1. Change and imperfection in the heavens (sunspots and lunar mountains),
2. New 'planets' orbiting Jupiter, and
3. Venus showing all the phases, like the moon.

Galileo also saw other interesting things, such as many stars that were too faint to see with the naked eye, and even the planet Neptune (that was not officially discovered until 1846!). Let us discuss these in turn, and examine their impact on the Aristotelian/Ptolemaic view.

Sunspots are observed as small dark patches on the surface of the sun. New ones appear from time to time, and they appear to slide across the sun's surface, as the sun rotates on its own axis (roughly once per 24 days). After a period of time (anything from a few hours to several months) they disappear again.



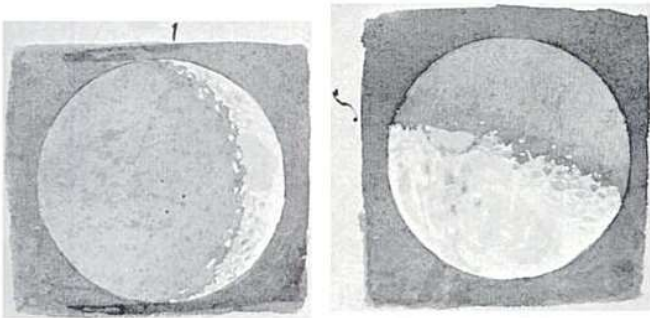
### **A Drawing of the sun by Galileo, showing sunspots**

Sunspots were seen and recognized by Chinese astronomers, as early as 346 BC. In the west they were also seen, but interpreted as the silhouettes of planets (Mercury or Venus) moving in front of the sun, or even as objects in our own atmosphere. A large part of the reason for this was surely Aristotle's teaching that the realm of the heavens is perfect and unchanging. The sun should be a perfect sphere of aether, and so can have no blemishes on its surface – especially ones that change over time. One contemporary of Galileo described sunspots as "filth on the cheeks of the sun".

Galileo was the first astronomer in the west to identify sunspots for what they are, namely areas of darker colour on or near the sun's surface. While this didn't directly threaten Ptolemy's model of the

universe, it did destroy a key idea of the Aristotelian cosmology that was associated with it (in peoples' minds).

Galileo also saw dark areas on the moon's surface that he (correctly) interpreted as shadows, due to mountains on the moon. More specifically, as the moon waxes and wanes (the illuminated part grows and shrinks), the boundary between the lit and dark portions of the lunar surface is not a clean arc, but rough and jagged. (See Galileo's sketches below.) Galileo inferred that the lunar surface is not perfectly smooth, as Aristotle taught, but rather very bumpy, with mountains, valleys and craters. Using his understanding of how shadows are formed by 3D objects, Galileo even estimated the heights of lunar mountains! This again did not attack Ptolemy's model directly, but it did refute some associated ideas of Aristotle.



**Some of Galileo's sketches of the moon**

Galileo's *Starry Messenger* also included his observations of 'new planets' that apparently orbited Jupiter. In a shrewd political move, Galileo named these the Medicean Stars, after the Grand Duke of Tuscany, Cosimo II de' Medici and his three brothers. (It doesn't hurt to make friends in high places.)

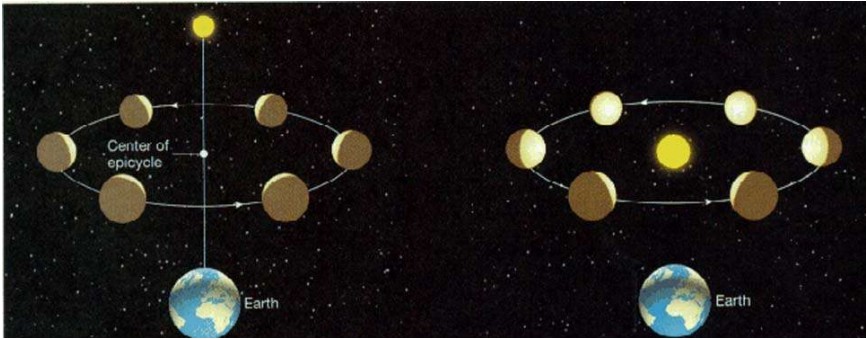
In the *Starry Messenger* Galileo didn't mention the Copernican view until the final page, when he apparently could not resist drawing parallels between Jupiter and the earth, in having their own orbiting planets:

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 an annual rotation about the sun. Some have believed that this structure of the universe should be rejected as impossible. But now we have not just one planet [the moon] rotating about another [the earth] while both run through a great orbit around the sun; our own eyes show us four stars which wander around Jupiter as does the moon around the earth, while all together trace out a grand revolution about the sun in the space of twelve years.

We see from this passage that the discovery of Jupiter's moons (as they're now called) did not refute the Ptolemaic system by any means. After all, one can easily add a few extra planets, orbiting Jupiter. But doing so would destroy the general rule that everything orbits the earth. With that tiny change made, it becomes fairly irresistible to modify the orbits of Mercury and Venus so that they actually orbit the sun, rather than orbiting points that are always between the earth and sun. In other words, this observation encourages us to move away from the Ptolemaic model and towards something like the Copernican one.

After publishing *Starry Messenger* in 1610, Galileo continued his work by observing Venus, and here finally he dealt the death blow to the Ptolemaic model. Recall that, for Ptolemy, Venus orbited (in its epicycle) a point that always lies below the sun, on the earth-sun line (see diagram below, left). According to this model, Venus is always between the sun and the earth, so that it will always appear as a crescent (like a crescent moon, but smaller) or as 'new' (totally dark). For Copernicus, by contrast, Venus orbits the sun, so that it is

sometimes on the far side of the sun, as well as coming around to our side. Consequently, Copernicus's model predicts that Venus will show the full range of phases, just like the moon – full, gibbous, half, crescent and new.



**The Phases of Venus according to Ptolemy (left) and Copernicus (right)**

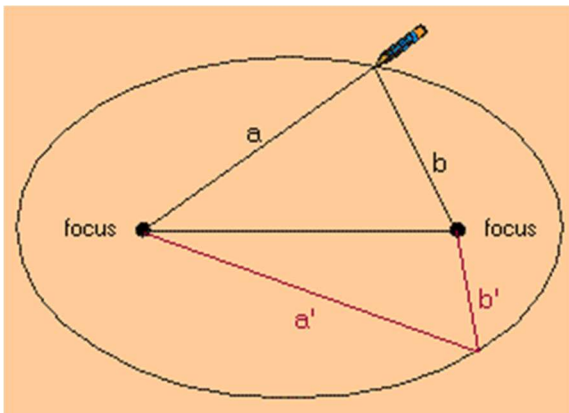
In refuting Ptolemy's model, however, Galileo did not prove the motion of the earth, for there were other alternative theories available. For example, Martianus Capella argued way back in the 5<sup>th</sup> century that Venus and Mercury orbit the sun (which in turn orbits the stationary earth) while all the other planets orbit the earth. And the great astronomer Tycho Brahe (1546 – 1601) proposed a model in which Mars, Jupiter and Saturn orbit the sun as well (which still orbits the stationary earth).

## 2.6 Johannes Kepler

Kepler (1571 – 1630) became a Copernican as a young man, and at the age of 25 (in 1596) published *Mysterium Cosmographicum*, the first Copernican book of astronomy since Copernicus's own *De Revolutionibus* (1543).

Kepler's most famous work of astronomy was the one mentioned above, the *New Astronomy* (1609). This is the book in which he laid out his theory that all the planets (including earth) move along ellipses rather than circles, around the sun which sits at one 'focal point' of the ellipse. This claim is known as Kepler's first law of planetary motion. Kepler also proposed a second law, concerning the variations in speed of a planet as it moves around its orbit – it gets faster as it approaches the sun, and slower again as it recedes from the sun.

The ellipse was a well-known mathematical curve, having been studied in detail by the great mathematician Apollonius of Perga (262 – 190 BC). It is a very simple curve, almost as simple as the circle, having the property that the sum of the distances  $a$  and  $b$  (see diagram below) is always constant, and equal to the major axis of the ellipse. Using this property, one can easily draw an ellipse by driving two nails into a board, and putting a loop of string around them. A pencil can then be put inside the loop, and pulled taut to form a triangle. If one then moves the pencil around the nails, keeping the string taut at all times, the resulting closed curve is an ellipse. The nail holes are special points, analogous to the centre of a circle, and are called the *focal points*. (We might, very loosely, say that the ellipse has two centres.)



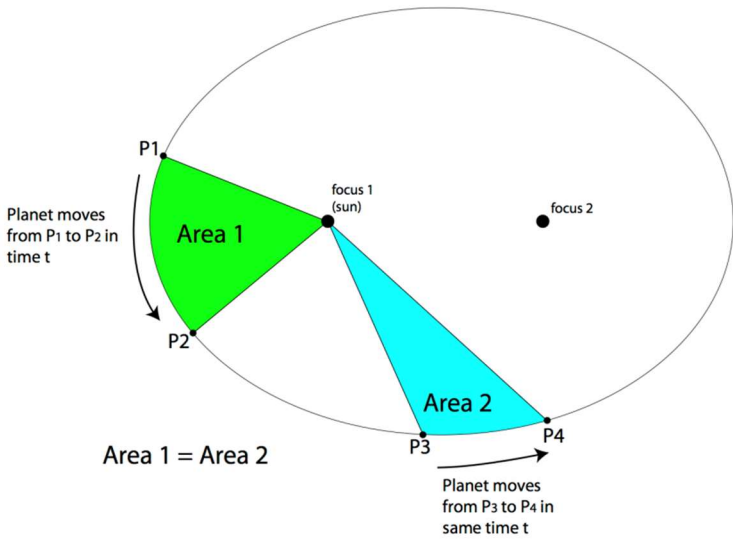
**The ellipse and its two focal points**



Recall that in Ptolemy's universe the planetary orbits were not quite centred at the earth, but at an empty point in space, close to the earth. (Such an orbit is called *eccentric*.) Ptolemy's placement of this centre was *ad hoc*. (In other words, it was arbitrary from a theoretical perspective, and chosen in order to fit the data.)

Kepler's placement of the sun in his universe was not *ad hoc* in the same way, since he placed the sun at a focus (focal point) of each planet's elliptical orbit, which is mathematically special, and theoretically definable. And this extraordinary elegance did not come at the expense of empirically accuracy. On the contrary, Kepler's model soon proved to be far *more* accurate than that of either Ptolemy or Copernicus.

A similar improvement in both elegance and accuracy came from Kepler's second law, shown below. To account for the varying speed of a planet around its orbit, Ptolemy had introduced a *third* point (in addition to the earth, and the centre of the planet's orbit) called the 'equant', stating that the angular speed of the planet is constant about its equant. Like the orbit centre, the equant was placed *ad hoc*, without any theoretical motivation. Copernicus hated the equant for this reason, but had to introduce similarly messy and *ad hoc* minor epicycles to achieve the same effect. Kepler needed no equant, or similar *ad hoc* device, but stated simply that the planet sweeps out equal *areas* in equal times.



### Kepler's 2<sup>nd</sup> ('equal areas') law

Kepler's third law appeared in a later work, and precisely related the period of a planet's orbit to its distance from the sun. Kepler's laws were later (1687) derived by Isaac Newton from his laws of motion and gravitation.

Not everyone was enamoured with Kepler's ellipses, as you might expect. The theory of circular orbits for the planets had been assumed by every astronomer since Plato, 2000 years earlier, and so was "settled science".<sup>1</sup> The astronomer Longomontanus, long-time assistant to the late Tycho Brahe, wrote to Kepler in 1604 to tell him that this whole business about ellipses was a "sordid insolence", that ran the risk of defiling the excellent reputation of the great Tycho. Longomontanus

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<sup>1</sup> The use of this phrase in this context is borrowed (along with many other things in this chapter) from Michael Flynn's *The Great Ptolemaic Smackdown*, available for free at <http://tofspot.blogspot.ca/2013/08/the-great-ptolemaic-smackdown.html>

recognized that Kepler had undertaken an enormous task in rebuilding the universe, and compared Kepler's job to the fifth labour of Hercules, who was ordered to clean the enormous stables of King Augeas (piled up with 30 years' worth of accumulated manure, from 1000 cattle.) According to the myth, Hercules achieved this task in a single day, by diverting two rivers through the stables. Kepler, on the other hand, had failed miserably at his task, and was still "submerged in shit in the Augean stable of old". Kepler replied indignantly to Longomontanus as follows:

If you are angry that I cannot eliminate the oval path, how much more ought you to be angry with the spirals, which I abolished. It is as though I have sinned with the oval I have left, even though to you all the rest of the ancients do not sin with so many spirals. This is like being punished for leaving behind one barrow full of shit although I have cleaned the rest of the Augean stables.

## 2.7 Galileo and Kepler

It was mentioned above that Galileo and Kepler were on friendly terms, and that Kepler was perhaps the first astronomer to whom Galileo confessed to being a Copernican. Another fun story is that, while Galileo was making his first discoveries with the telescope, he communicated his observations to Kepler (and others) in the form of anagrams. For example, after seeing the phases of Venus, he wrote "Haec immatura a me jam frustra leguntur oy" which means something irrelevant in Latin, but is an anagram of "Cynthiae figuras aemulatur mater amorum", meaning "The mother of love [i.e. Venus] imitates the shape of Cynthia [the moon]".

Kepler also assisted Galileo after Galileo published *Starry Messenger*. Aristotelian scholars, as one might expect, were quite hostile to

Galileo's discoveries, and claimed that his alleged discoveries were mere optical illusions, i.e. artefacts of the telescope itself. For example, they alleged that the new planets orbiting Jupiter were in reality just points of reflected light within the telescope. Galileo responded impatiently that he would pay a huge reward to anyone who built a telescope that could create such points of light around a planet other than Jupiter (e.g. around Mars). He also asked Kepler for his opinion, and Kepler quickly published a short tract, *Conversations with the Starry Messenger* (1610), that enthusiastically endorsed Galileo's discoveries (even though Kepler did not gain access to a telescope himself until later).

One of the chief opponents of Galileo's observations was Martin Horkey, a former student of Kepler. He looked through Galileo's telescope at objects on the earth and judged it to be marvellous, but claimed that "in the heavens it deceives". He argued for this by pointing out that some familiar stars appear double through the telescope, and that a star in the Great Bear constellation also has an apparent cluster of 4 little stars nearby, when viewed through the tube. Horkey published a tract attacking Galileo's observations as fraudulent, and claiming that the only use of the imaginary planets was to gratify Galileo's thirst for gold and notoriety. Horkey wrote to Kepler, telling him of Galileo's lies and deceit, but Kepler replied, "Since the demands of honesty have become incompatible with my friendship for you, I hereby terminate the latter."

While Galileo sought (and received) the support of Kepler in his research, he did not always return the favour. Kepler asked for, but never received, the opinion of Galileo on his 1609 *New Astronomy*, which contained his theory of elliptical orbits. Also, Kepler invented an improved astronomical telescope in 1611, whose basic design is still commonly used today, yet Galileo never used Kepler's more powerful telescope.

## 2.8 The Parallax Problem Still Unsolved

With the naked eye, a bright fixed star appeared to have a diameter of around 2 minutes per arc (120 arc-seconds). This observation, you will recall, led to the problem for Copernicus that the fixed stars must be absolutely huge. Viewed through a telescope, Galileo initially claimed that a fixed star had no apparent size at all, but was a mere point of light. Later, however (in 1632) he admitted that fixed stars did still appear as discs through his telescope, although the apparent diameter had shrunk to a mere 5 arc-seconds, i.e.  $1/24$  of their naked-eye size. This reduction in the apparent size of star, when a telescope is used, is rather curious, but Galileo believed that it revealed some defect of the eye itself. (As far as I know, Galileo never suggested that the telescope itself might be deceptive – and one can understand why, with the likes of Martin Horky around.)

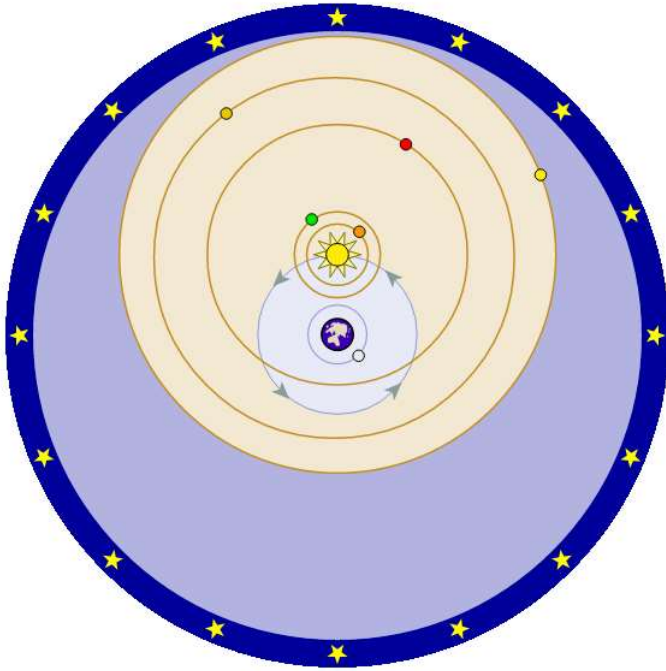
With a reduced apparent star size, one might think that the problem of giant stars would be reduced, but it was not so. For Galileo's telescopes, with their much greater accuracy than a naked eye, still revealed no annual stellar parallax. To account for this absence, the distance to the stars had to be enormously increased from even the minimum 7,000 A.U. estimate by Tycho. (By something like a factor of 20, I think.) Thus, as a result of the telescope, the stars remained just about as ridiculously large as before, but they became even more absurdly distant.

## 2.9 Tycho's Compromise Model

In the popular understanding of 17<sup>th</sup> century astronomy, the battle was between two theories. One was the creaky old theory of Ptolemy, supported by dogmatic religious authorities, and the other was the elegant theory of Copernicus, supported by creative young scientists,

such as Galileo and Kepler. In fact, however, there was a third theory, and for many astronomers and religious leaders at the time it combined the best features of the other two models, while avoiding their shortcomings.

The third model was the work of Tycho Brahe (1546 – 1601), who was known chiefly for his incredible skill as an observer of the heavens. He proposed it in the late 1570s and it is known as the Tychonic model, or the geo-heliocentric model. Tycho was convinced by Copernicus that the sun must be the (approximate) centre of the planetary orbits, apart from the moon. Thus Mercury, Venus, Mars, Jupiter and Saturn all orbit the sun. However, he saw no additional advantage in claiming that the earth is also a planet, orbiting the sun. Instead, one can keep the earth stationary, and make the (moon and) sun orbit the earth, while everything else orbits the sun. In this way, the model of Tycho is equivalent to that of Copernicus in all *relative* motions. In particular, Tycho's model has the same elegant explanation of retrograde motions as that of Copernicus.



### The Tychonic System

Thus, when Galileo observed Venus, and discovered (from its phases) that it was sometimes behind the sun, this observation confirmed the Tychonic system just as much as the Copernican. It certainly did not prove the motion of the earth.

The Jesuits (or 'Society of Jesus', a Roman Catholic order of intellectuals) embraced the Tychonic system pretty soon after Galileo's telescope refuted the Ptolemaic system. Through their influence, the Catholic Church officially adopted the Tychonic system from 1611 – 1620.

The big advantage of the Tychonic system over the Copernican was that it had a stationary earth. In this way Tycho avoided the most serious

objections raised against the Copernican view, discussed above, such as the missing stellar parallax, the Copernican abyss, and the giant stars.

## 2.9 Galileo and the ocean tides

The existence of Tycho's model, as a competitor to the Copernican model, meant that no observation of the positions of celestial objects could possibly prove the Copernican system, or reveal the earth's actual motion. Any observation that fitted the Copernican model would fit the Tychonic model equally well. Desperate to prove the earth's motion, Galileo turned to evidence of another sort.

Galileo had an 'Aha!' moment when he saw a barge carrying a large tank of water. When the barge slowed, the water moved forward in the tank, and then sloshed back and forth for a while. Galileo saw, in the regular motion of the water back and forth, a good analogy with the regular oscillation of the world's oceans (i.e. the tidal motions). Just as the water in the tank was induced to move by the motion of the ship, Galileo inferred that the tides are caused by the earth's motion. Here at last was proof! (Take that, Tycho!)

This was the basic idea, but how are the details going to work? For one thing, Galileo's observation of the ship showed him that motion itself doesn't cause the water to start sloshing around – you need a *change* of motion for that. If the ship goes in a straight line, at a constant speed, then the water appears stationary in the tank. But the earth doesn't ever change speed, does it?

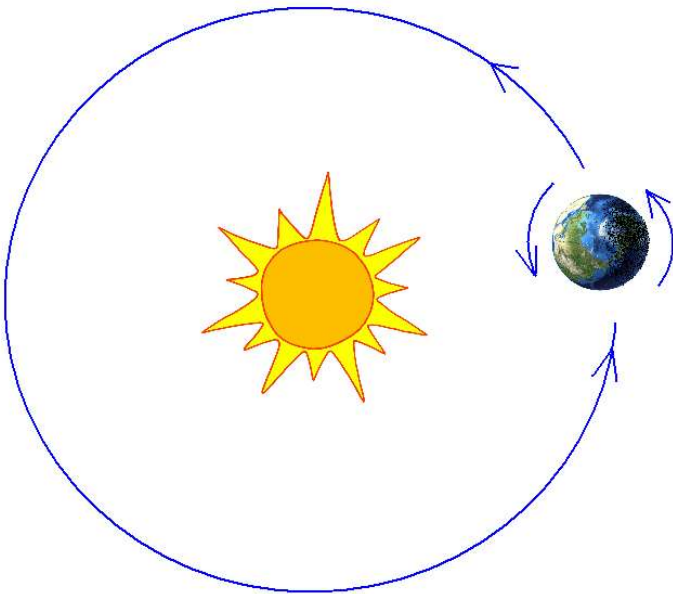
Well it does, said Galileo, since the earth has two separate motions that (at a given point on the surface) are sometimes in the same direction, and sometimes opposite. To see this, imagine you're viewing the earth from the celestial north pole, looking down on the earth and its orbit.



You would see the earth rotate counter-clockwise about its own axis, and also orbit counter-clockwise around the sun. (See diagram below.)

Now think about some point on the earth's surface, far from the poles. During night-time at that place, you can see in the diagram that the two rotary motions are aligned, in the same direction, so one is going extra fast at night. During the day, one is on the opposite side, now facing the sun, and the two speeds are in opposite directions. Hence one has slowed down a bit.

In other words, at any given spot there is a daily rhythm of acceleration and deceleration which is too slight to notice directly, in our own bodies, but whose influence on the oceans *is* visible in a daily rise and fall of a few feet in sea level.



**The daily variation in speed, at a point on the earth, causes the tides (says Galileo)**

Now Galileo was not the first to offer an explanation of the tides. Traditionally the tides were thought to be caused by the moon in some way, since high tides occur (approximately) when the moon is at its highest point in the sky, and 12 ½ hours later. Low tides occur when the moon is rising and setting. Following in this tradition, Kepler had speculated that the earth and moon might exert something like a magnetic force of attraction on each other, and that this force of the moon on the earth's oceans is the cause of the tides.

Galileo rejected this lunar theory, and in his great work (the *Dialogue*) where he presented his best arguments for Copernicanism, the centrepiece is his argument that only the earth's motion can be the cause of the tides. Galileo wrote:

Lately a certain prelate has published a little tract wherein he says that the moon, wandering through the sky, attracts and draws up toward itself a heap of water which goes along following it, so that the high sea is always in that part which lies under the moon. And since when the moon is below the horizon, this rising nevertheless returns, he tells us that he can say nothing to account for this effect except that the moon not only retains this faculty naturally in itself, but in this case has also the power to confer it upon the opposite sign of the zodiac.

Galileo rightly points out that the lunar theory seems to predict one tide per day rather than the two that are observed. Unfortunately, however, Galileo's theory also seems to predict one high per day rather than two, as each day has only one period each of acceleration and deceleration. (Galileo dismissed this anomaly as the result of additional factors, including the shape of the sea floor and its depth.) In addition to this criticism, however, Galileo also pointed out that the *mechanism* of the moon's supposed influence is completely unknown.

But that concept is completely repugnant to my mind; for seeing how this movement of the oceans is a local and sensible one, made in an immense bulk of water, I cannot bring myself to give credence to such causes as lights, warm temperatures, predominances of occult qualities, and similar idle imaginings.

In other words, Galileo is not going to consider seriously the idea that the moon acts upon the oceans, from hundreds of thousands of miles away, by means of a secret, invisible force. Galileo also pointed out that the moon has no observable effect on a tank of water. The water in a tank does not follow the moon's path through the sky. The only way to get the water in a tank to slosh back and forth is by *moving* the tank.

In general, Galileo's scientific colleagues found this key argument for the earth's motion unconvincing, and church authorities tended to agree. Galileo had no proof for the motion of the earth.

## **2.10 Galileo and the Church**

Initially, the Church received Galileo's new observations with his telescope warmly, although many Aristotelian scholars were hostile. It did not help that Galileo apparently had a rather large ego, and (according to his enemies) a tendency for self-aggrandisement. In short Galileo made enemies, and they determined to cause him trouble. Chief among these enemies was the Aristotelian philosopher Lodovico delle Colombe, who had tangled publicly with Galileo concerning the 1604 supernova and the mountains on the moon, among other matters. The dispute involved personal insults, such as Galileo referring to delle Colombe as 'nostro colombo' ('our pigeon') and as 'pippione' (which literally meant 'young pigeon', but also meant 'fool', or 'jackass').

Delle Colombe assembled a group of Aristotelian philosophers and churchmen who shared his hatred of Galileo, and plotted his downfall. Galileo's friend Cigoli got wind of this, and in 1611 wrote to Galileo warning him that a group of his enemies were meeting regularly in the house of the Archbishop, "in a mad quest for any means by which they can damage you." (Cigoli referred to this group as the 'Lega del Pippione', i.e. 'the Pigeon League'.)

The Pigeon League included a Dominican friar, Tommaso Caccini, who in 1614 denounced Galileo from the pulpit, arguing from Holy Scripture that the sun (not the earth) stood still for Joshua (see Joshua 10:13 in the Bible). This action didn't go anywhere, as Tommaso's boss quickly told him to stop being a fool, but then another Pigeon Leaguer and Dominican, Niccolo Lorini, obtained a crucial document that would indirectly get Galileo into a lot of trouble.

The document was a copy of a letter, written by Galileo to Benedetto Castelli, one of his former students and also a Copernican. In the letter, Galileo argued that Copernican astronomy is compatible with the Christian Bible, essentially on the grounds that the very few passages that seem to imply a stationary earth can be interpreted non-literally. Castelli was very pleased with the letter, and so made copies of it and passed them around. However, someone gave a copy to Lorini.

There wasn't anything very novel about the methods Galileo used to interpret the Holy Scripture, but as a mere mathematician Galileo was in no way qualified to do the work of a theologian. So Lorini passed the letter to the Roman Inquisition, along with a cover letter suggesting that the Galileans might need to be punished for interpreting the Bible "according to their private lights and in a manner different from that of the common interpretation of the Fathers of the Church".

Lorini's complaint against Galileo was dismissed by the Inquisition, on the grounds that Galileo's letter, though presumptuous, didn't contain

anything unorthodox. Unfortunately for Galileo, however, Lorini's complaint coincided with the publication of a book by Paolo Foscarini, which also argued for the Copernican theory being compatible with Scripture. In April 1615, Cardinal Bellarmine of the Inquisition wrote to Foscarini to tell him that he could not 'hold or defend' the Copernican hypothesis without "a true physical demonstration that the sun does not circle the earth but the earth circles the sun". Also, Bellarmine believed that no such demonstration existed at the time, and this being so, it was not permitted to interpret Scripture as Foscarini (and Galileo) were doing.

With the issue of Copernicanism having been brought to their attention by both Galileo and Foscarini, the Roman Inquisition assembled a committee of 'qualifiers' – theologians who were asked to judge whether the Copernican doctrines were heretical. In 1616 the Qualifiers delivered their report, finding that Copernicanism is formally heretical, being opposed to the literal meaning of the Biblical text. Though the ruling did not mention Galileo by name, and was not binding on the Church, the Pope ordered that Galileo be summoned to a meeting with Bellarmine and be instructed not to 'hold or defend' the Copernican model as a physical fact, rather than a mere mathematical convenience. At the meeting, Galileo agreed to obey this ruling, which was just as well since had he resisted, Bellarmine was to issue a formal injunction to the same effect, which would carry a threat of imprisonment if he disobeyed it.

At Galileo's request, and in response to rumours that Galileo had been censured, Bellarmine wrote him a certificate to confirm that he had not been accused of anything, nor forced to abjure any opinion, nor do any penance.

Galileo was reasonably happy with this result, as it allowed him to continue searching for a real proof of the earth's motion. Bellarmine himself had said, in his letter to Foscarini, that the scriptures that

seemed to indicate a stationary earth could be reinterpreted, if someone were to demonstrate a moving earth. Then in 1623 Galileo received some excellent news: his good friend Cardinal Maffeo Barberini had been elected Pope (Urban VII).

Later that year Galileo published another book, *The Assayer*, a polemic against Orazio Grassi, a mathematician who argued that comets orbit the sun along a non-circular path – contrary to the Copernican view that all heavenly bodies move in circles. Galileo argued therefore that comets are a phenomenon in the earth's atmosphere. Once again, Galileo was rather savage in his language attacking Grassi, and the book made enemies even among the Jesuits, who had supported Galileo at one time.

In the following year, 1624, Galileo met several times with his friend Pope Urban VIII, who suggested that he write a new book setting out the arguments for and against the Copernican and Ptolemaic systems. In particular, the Pope required that Galileo include consideration of some of the Pope's own arguments. Galileo started to work on this book, making it a conversation between three friends, Salviati (Galileo's mouthpiece), Sagredo (a neutral participant) and Simplicio (an Aristotelian, based on delle Colombe).

In 1632 the book was published, as *Dialogue Concerning the Two Chief World Systems*, with the Pope's permission, and after being cleared by censors. The book was a popular success, but unfortunately for Galileo the Pope perceived that Galileo had insulted him, by putting the Pope's own arguments into the mouth of the character 'Simplicio'. Not only was Simplicio a blundering fool, whose arguments got destroyed, but his name in Italian could mean 'simple' (or even 'simpleton'). Moreover, despite Galileo's assurances that the book would be an even-handed treatment of the arguments on both sides, it was very clearly a full-blooded defense of the Copernican model as physically real.

Due to this and other political reasons, in 1633 Galileo was again tried by the Inquisition, and this time the outcome was much worse.

The meeting between Galileo and Bellarmine in 1616 now came back to bite Galileo, as a good case could be made that Galileo had deliberately disobeyed Bellarmine's instruction not to "hold or defend" the moving-earth theory. Also, there is the rather mysterious fact that the minutes of that 1616 meeting, when retrieved in 1633, recorded that Father Segizi, the Commisary-General of the Holy Office, *issued the formal injunction* to Galileo. There is considerable doubt as to whether this record is true, as the Pope's order was to issue the injunction only if Galileo rebuffed Bellarmine's instruction, and Bellarmine makes no mention of the injunction in the certificate given to Galileo. In addition, the record lacks the necessary signatures (including Galileo's) that would be legally required. There are various theories offered to explain these irregularities, but it is likely that Segizi himself (a Dominican like Tommaso and Lorini) added a false record to the minutes, as the file was kept in his office. (N.B. Bellarmine died in 1621, so he could not give his account of the 1616 meeting.)

The record of the injunction having been issued to Galileo in 1616, whether genuine or forged, was a major problem for Galileo, as it was clear that Galileo had disobeyed the injunction, which carried a penalty of imprisonment. It seemed to be an open-and-shut case, and the Pope wasn't inclined to intervene on Galileo's behalf, due to the perceived insult mentioned above.

The Inquisition therefore found Galileo 'vehemently suspect of heresy' (a lesser charge than heresy itself) Galileo was sentenced to house arrest for life, and his book was 'placed on the Index' (banned). He was able to continue his work, however, living for a while with the Archbishop Piccolomini in Siena, before moving back to his own villa in Florence.