# How Do Things Move In The Sky?

The account in your text of planetary motions, and pretty much every other astronomy text, is sort of a just-so story. It retrofits a story of what must have happened, what people must have been motivated by, what they must have been up to, and how it was all guided by a notion of science that forces the story to conform to the “scientific method” (whatever that is) and is, historically, completely wrong.[[1]](#footnote-1)

There is one feature of The Conventional Story that is central – the distinction between science and not-science is that science makes testable predictions and, if the predictions are wrong, then the hypothesis is wrong. That is not the same thing as not being scientific, however. Some of the most important advances in the history of science were driven by predictions that turned out to be wrong. A hypothesis can be scientific without ending up as part of the accepted body of scientific knowledge.

Even this, however, is forcing a modern point of view onto the ancient world and nothing could be further from the truth. The central role of experiment and observation in science wasn’t formalized until Francis Bacon took it up in the late 16th/early 17th century England. He was the first to rigorously and consistently insist on empiricism and inductive logic as ways to discover the truth, roughly 1000 years after people first started thinking about the problem.

It is true that Aristotle did advocate empiricism as well, but the fact that he thought women had fewer teeth than men shows that he wasn’t all that good at it. He maybe looked in 2 or 3 mouths and called it a day. The idea of statistical variation, means and standard deviations, was unknown to him. Aristotle also rejected inductive logic. It is hard to argue with his reasoning. Induction involves looking at a number of individual cases and abstracting from them a general rule. Aristotle argued that no number of specific cases was sufficient to prove a general conclusion, and he was right about that.

Suppose you walk out of the building and the first ten people you see have blonde hair. Are you justified in concluding that all students are blonde? Clearly not. So Aristotle kind of had a point. For most of the ancient world (there were a few exceptions), the only path to truth was rigorous deductive logic from a set of assumptions that were obviously true. You reach truth primarily by thinking, rather than investigating.

But to think about a physical phenomenon, you first have to see what it is. The fact that things in the sky move relative to the stars (the Greeks called them *planetos*) had been known to the ancient Egyptians and records of their positions (as precise as possible with the tools of the day) had been kept since at least the Babylonian Empire. This was mostly for the purpose of divination, and the dirty secret of astronomy is that most of its history is shared with astrology.

It is appropriate to think of this history as one of the development of an understanding of science as distinct from philosophy and divination, with its own standards of evidence and argument. However, it is *wildly inappropriate* to impute that motive to them. That is definitely not what they thought they were up to. They were doing their own things for their own reasons and it is only at the end that you can look backward and find a story about the development of science.

So let’s see what they were trying to describe.

## I. Collect some data by just observing the sky

The ancient world had the luxury of watching planets for centuries but we don’t so we will use the simulator. Fire up Stellarium and groom it a bit.

* Turn off the ground, the atmosphere and the cardinal points to eliminate distractions.
* Turn on equatorial mode to eliminate the wild and distracting swinging about of the default azimuthal mode.
* Since we are mainly interested in the planets, the star names are distracting and in the way. In the left side menu, there is a button that looks like a star with a speech balloon containing a star, a planet and a galaxy (third down from the top). Clicking that will bring up the Sky and Viewing Options window. On the SSO tab, under Stars, uncheck the box for Labels and Markers. On the DSO tab, uncheck everything that is checked.
* Close the settings window and go to the bottom screen toolbar. There is a button that looks like things falling out of the sky. This labels the positions where meteor showers occur. Turn it off. Now all the labels except those for the Sun, Moon planets, and maybe a few asteroids should be gone.
* Zoom WAY out. As far out as you can go. You’ll end up with a sort of fisheye view of most of the sky so things will look a little funny, but at least we won’t have to keep reorienting it as planets move in and out of view. That fuzzy circle in the middle is the Milky Way.

**A.** On the bottom screen menu, there are some video playback controls (extreme right). ►► and ◄◄ are fast forward and fast reverse. Clicking them multiple times increases the playback speed in that direction. ► resets it to real time speed.

You can vary the playback speed as needed. Your job is to carefully observe the motions of the planets as they go around the sky. What direction do they generally go? Do you notice anything weird about what they do? Pay attention to the details.

**B.** Now observe the Moon and the Sun. Do they behave in the same way as the planets?

***Discuss your results with your instructor at this point***

## II. How can we describe this? The Geocentric Model

The weird thing you have just discovered is something called *retrograde motion.* The most natural thing in the world, and the thing that the ancient world generally assumed, was that what you see is what is real. Things appear to be moving because they are. We do not have a sensation of movement so we are not. Some things look like they go backwards from time to time because they do. And some things look like they don’t because they don’t.[[2]](#footnote-2)

### Are we trying to find out what is really happening in the sky?

No.

The ancient world had a peculiar point of view on the issue of explanations. They rejected the very idea that it was possible to know what is happening way up there. A 6th Century Neoplatonist philosopher, Simplicius of Cilicia (who was an astrologer), stated it succinctly in his *Commentary on the Four Books of Aristotle’s Book on the Heavens*:

“Plato lays down the principle that the heavenly bodies’ motion is circular, uniform and perfectly regular*.* Thereupon, he sets philosophers the following problem: What *circular motions, uniform and perfectly regular,* are to be *admitted as hypotheses* so that it might be possible to *save the appearances* presented by the planets.” [Emphasis added]

From a modern point of view, this is a decidedly odd way of thinking. We are not going to experiment until we find what works. We will only allow ourselves to consider steady, regular movement around circles and nothing else. The Greeks believed the heavens were perfect and unchanging, and circles were the most perfect geometric figure, so circles are the only appropriate shape for the heavens.

But even stranger is this odd phrase “save the appearances.” Greek philosophers believed what was really happening in the heavens was intrinsically unknowable. So their goal was simply to make a conceptual machine that did the same thing the sky did, but they never argued that their machine was truly the way the sky worked. This is definitely not a scientific effort. The purpose is not explanation but simply to be able to predict future positions.

The first person to take a serious crack at it was Eudoxus of Cnidos in the 4th century BCE. Everything he wrote has been lost so we know very little about him other than comments from other authors. He imagined planets attached to crystal spheres that rotated on axles fixed to the sphere of the stars. That way, they each have their long term motion around their axle, but also share the daily motion of the stars.

It is impossible for this machine to be real and Eudoxus knew it. After all, as soon as you try to add a second planet to the first one, one of them has to have an axle that goes through the other’s crystal sphere and the whole scheme falls apart – unless, of course, you don’t actually expect this thing to be real, but just a tool for calculating.

By the time of Ptolemy (who was an eccentric astrologer), in the 2nd century BCE, the whole idea of imagining an actual machine had fallen away. Planets were assumed to have certain motions because that is what they did, with no deeper explanation. Ptolemy’s model is a truly glorious machine of planets on circles that are on other circles. But its only purpose was to predict where planets would be in the future.

Adopting Ptolemy’s model as the absolute truth of what was really up there didn’t happen until Thomas Aquinas (who was an astrologer) adopted Aristotle into Catholic dogma in the 13th century.

### How does the machine work?

Start the NAAP lab, select Solar System Models, and under Geocentric Model bring up the Ptolemaic system simulator. This is a vastly simplified version of Ptolemy’s model, with only the Earth, the Sun and one planet.

The blue dot is the Earth, which is stationary but not quite at the center. The purple dot is the actual center of everything. Motion on the large circle is centered on the purple dot, not on the Earth. The green cross is called the equant. The small circle (the epicycle) moves uniformly around the equant, but *not uniformly* as seen by either the Earth or the purple dot. This will turn out to be profoundly important to Copernicus.

The small rectangular window at the bottom depicts where the planet and Sun would be as seen from Earth against the background of the Zodiac stars.

**A.** Run this model for a little while. Explain how it accounts for retrograde motion of the planet. If it helps to see what is going on, you can pause the animation, slow it down, or click and drag on a planet so you can move it forwards and backwards around a point.

**B.** Remembering what you observed in part I, why is there no epicycle for the Sun or Moon?

Even though Ptolemy did not assume his machine was real, Aquinas did. So let’s use it to make some predictions.

**C.** For the ancient world, the planets stopped at Saturn. Even though Hipparcos observed Uranus, it moved so slowly he thought it was a star, and Neptune is not visible at all without a telescope. Mars, Jupiter and Saturn can be seen at any time of night, depending where they are in their orbits. Mercury and Venus can only be seen in the morning before sunrise, coming up just before the Sun, or in the evening after sunset, following the Sun down. They are never seen in the middle of the night.

The geocentric model reproduces this behavior by imposing a restriction on Venus and Mercury that the rest of the planets don’t have to obey. The NAAP simulator allows you to select different planets and look at the model for each. What is the extra restriction on Venus and Mercury compared to Mars or Jupiter? If you can’t see it right away, try turning on the Earth-Sun line and see if that helps. How does that account for the difference in when during the night we are able to see the planets?

This difference is critically important in making a correct prediction. One of the first things Galileo (who was an astrologer for money though he didn’t believe in it) did with his shiny new telescope was point it at Venus because it was the brightest planet. Set the simulator up for Venus. Galileo saw that Venus had phases, similar to the Moon.

**D.** Run the simulation until Venus is at its furthest point from Earth, and draw a sketch of the system showing where the Earth, Venus and Sun are located at that time. Using what you’ve learned about phases, what should the phase of Venus be? Explain.

**E.** Run the simulator until Venus is closest to Earth. Make a similar sketch and determine the phase of Venus at that point. Explain. How is this different from the Moon’s phases?

**F.** Using the same half dark/half light ball we used for the Moon phases activity, simulate the motion of Venus in the geocentric model of Ptolemy (you could also use your sketches from Part I of Phases of the Moon). So your ball should go in a circle in between the Earth observer and the Sun/Window. Does Venus go through the full cycle of phases?

***Discuss your results with your instructor at this point***

**G.** Return to Stellarium and search for Venus. Zoom WAY in. At some point, Venus should change from just a bright circle of light to an actual image of the planet. Zoom in far enough so that you can get a clear look at its phase. Now run time forward so you can observe Venus’ appearance over time. Based on what you see, in what way(s) does it compare to the predictions of the Geocentric model. What do you (and Galileo) think of Ptolemy’s work based on what you see?

**H.** Now search for Mars and run time forward. This is probably going to be easiest to see what is going on if you do not use fast forward. Instead, go to the Day/Time button on the left side toolbar and step ahead by months. Does it behave the same as Venus? Explain.

**I.** In the geocentric model, Mars is doing something similar to Venus, but with a few differences. What ranges of phases does the geocentric model predict for Mars? The simulator might help. Is that what you saw?

***Discuss your results with your instructor at this point***

## III. How Can We Describe This? The Heliocentric Model

There is an enormous mythology built up around Copernicus and Galileo. You were probably taught some of it in middle school, but much of it is simply untrue. Galileo’s famous Leaning Tower of Pisa experiment, for instance, is physically impossible given what we now know about air resistance, and probably never happened. He was known at the time to be kind of a slippery character who couldn’t always be trusted.

Copernicus is said to have been the originator of the Sun-centered model. He was not. Heliocentrism was a minority opinion among astronomers since at least the time of Aristarchus of Samos around 200 BCE.

### Did the geocentric model get less and less accurate over the centuries?

No.

It worked as well as it ever had, which was tolerably well by the standards of the day. After all, it was the same math describing the same motions. Whatever other advantages heliocentrism might have, greater accuracy was not one of them. Copernicus’ model was about as accurate as Ptolemy’s. Sure, Ptolemy’s model had to be trued up from time to time with new starting positions as the predicted positions drifted out of alignment with the actual observed positions, but so did Copernicus’ and so do ours today. They all have to be reset from time to time.

### Did the geocentric model need more and more epicycles to keep it accurate?

No.

The fact that it didn’t lose accuracy should make you suspect this claim is wrong. In fact, all the pieces of the geocentric model are interdependent. If you change one part, the changes ripple through to all the other parts. The version produced by Ptolemy is probably about as optimal as a geocentric model can be. Any changes would make it less accurate overall rather than more.

### Did Copernicus get rid of all that complicated epicycle business?

No.

Some have claimed that Copernicus eliminated all the epicycle business and produced a model that was much simpler. He did not. Copernicus’ heliocentric model still has epicycles. This is because he agreed with the ancient Greeks that celestial motion had to be steady, uniform and in circles. As we will see later, the orbits are not in fact circles, they are ellipses, and the speed of the planet varies as it goes around its ellipse. In order to make uniform circular motion behave like nonuniform elliptical motion, Copernicus needed epicycles, as you can see from a page of the manuscript below. In fact, he needed about as many epicycles as Ptolemy needed, so greater simplicity was not a feature either.[[3]](#footnote-3)

graph of model with epi cycle 



### So what was it Copernicus thought he was doing?

What appears to have disturbed Copernicus was that Ptolemy’s version of geocentrism, in order to achieve its accuracy, had to introduce a *nonuniformity*. If you look at the simulator, there is a green cross indicating the position of a point called the *equant*. For each planet, there is a big circle (the *deferent*) on which a smaller circle (the *epicycle*) goes around. The equant is the center of the deferent circle. So the center of the epicycle is orbiting the equant, not the Earth.

The Earth is not at the equant. It is displaced from the center of the motion. This means the planet is sometimes closer to the Earth than at other times. It wobbles around like a wheel with an off center axle.

For now, we are going to ignore the ellipses and use a greatly simplified Copernican model that will get at the main points without the unnecessary but relatively minor complications of epicycles. We need to explain retrograde motion at least as well as Ptolemy did, and we need a better explanation of phases for planets like Venus.

**A.** Start the NAAP heliocentric model simulator (called “planetary configuration simulator” for some reason). You’ll find it under Solar System Models. By default, it is set so that you (on the blue planet) are closer to the Sun than the grey planet. So this would be for a planet like Mars, Jupiter or Saturn. As with the geocentric simulator, you can run the simulation like a movie, or pause it and click and drag on a planet. There are also presets for orbit sizes for each of the planets. Beneath the simulator, you can see where the Sun and planet would be located against the stars as seen from the Earth.

Choose Earth for the observer’s planet and Mars for the target planet. Run the simulator for a while, observing when retrograde motion occurs. What is happening with the planets at these times? How does the model account for retrograde motion?

**B.** Now set the target planet to Venus. Is its retrograde motion accounted for in the same way?

**C.** We saw that the geocentric model accounted for Mercury and Venus staying close to the Sun by the ad hoc requirement that the Sun, the Earth, and the center of the epicycle always be connected by a straight line. Mars, Jupiter and Saturn did not have this restriction and could be seen in the middle of the night as well as morning and evening. How does the heliocentric model account for these observations? It might help to turn on the elongation angle.

**D.** So now we have seen that the heliocentric model accounts equally well for retrograde motion. Let’s check the phases of Venus, since geocentrism totally failed on that. You’ll have to modify your half and half ball model a bit to do this. We can’t let the windows be the sun anymore without having to go outside the building for half the orbit. So pick a spot in the room that will be the sun and place an object there. You’ll carry your ball around that object in such a way that the light side is always pointing at the object. The person playing Earth will have to be further away from the object than the ball is. Does heliocentrism properly account for the phases of Venus? Explain.

**E.** Heliocentrism makes an additional prediction related to the phases of Venus. Where is Venus located relative to the Earth and Sun when it is full? How about when it is New? Looking at those phases of Venus in Stellarium, can you see any other evidence that these phases are in the correct positions?

***Discuss your results with your instructor at this point***

The heliocentric model makes an additional prediction that the geocentric model does not address – the planetary orbits must be specific sizes. In the geocentric model, a planet could go fast around a big circle or slow around a small circle and either would work. But that cannot work in the heliocentric model.

To see how this works, we can use the NAAP simulator to find where Venus, Earth and Sun are at two specific times called *greatest elongation*. There are two of these, one when the planet is east of the Sun and one when it is west.

**F.** Check the box “Turn on elongation angle” and uncheck the box “Snap to events when dragging planets.” This will show the angle between planet and Sun as seen from the Earth. That angle is called the *elongation*. What happens at greatest elongation?

**G.** Imagine three lines that connect Earth to Sun, Sun to Planet, and Planet to Earth. These form a triangle, but what kind of triangle is it at greatest elongation: acute, obtuse or right?

**H.** The NAAP simulator gives you a value for the greatest elongation angle but we can get a much better one from Stellarium, if we first add something to it add something to it. Go to the side toolbar, select configuration, and go to the plugins tab. Choose the angle measure plugin, and check the box “Load at Startup.” then restart Stellarium. Now you’ll have a new tool to measure angles. It will be on the bottom toolbar to the left of the video controls.



Turn off the distractions as usual, put Stellarium in equatorial mode, and search for Venus. Make sure you are zoomed out far enough to see both Venus and the Sun at the same time. Turn on the angle measuring tool. Click and drag between the center of Venus and the center of the Sun. You will see the elongation angle in degrees, minutes and seconds. What value is it today?

**I.** Now we need to go forward in time to find the greatest elongation. Bring up the Date and Time tool and go forward by months until you see about when the distance between the Sun and Venus has stopped getting bigger and started getting smaller, or the other way round. Then zero in on the turnaround time by going forward or backward by days. You’re going to have to keep remeasuring the angle to find its biggest value. What is that value and on what date does it happen? Is it Eastern or Western elongation (turn the cardinal points back on if they are off)?

**J.** Now we need to do a little math. For a right triangle, the trigonometric function sin θ is defined as:

To make this work in a calculator, we have to change from Stellarium’s degrees, minutes and seconds to decimal degrees. There are 60 seconds in a minute and 60 minutes in a degree, so this is straightforward. Take the number of seconds, divide by 60 and add to the number of minutes. Divide that by 60 and add to the number of degrees. Now you have the angle in decimal degrees. Look at the geometry in the NAAP simulator so see which distance is the hypotenuse and which is the side opposite. You can look up the radius of the Earth’s orbit in km for this purpose. After you’ve calculated a value for the orbit of Venus, you can also look it up and assess your answer. If Venus were at *any other distance*, the heliocentric model would necessarily be wrong

### Does an idea have to be right to be scientific?

No.

The Geocentric model is just as scientific as the heliocentric model because they share a common trait – each of them makes predictions that, if wrong, mean that the model cannot possibly be true. Each contains the seeds of its own potential destruction. This property is called *falsifiability*.

### The Galileo Affair: Why was the Church so Put Out?

More people know more things about Galileo and the church that are completely wrong than any other episode in the history of science. It is not in the main line of development here so I won’t go into detail. I’ll just correct a few of the biggest myths.

1. Was Copernicus afraid of the Church? No, not really. Although his major work did not appear until the year of his death in 1543, he had written a description of it the same year, 1510, when he completed it. The Church was aware of it for over 70 years after Copernicus’ death and seemed to have no problems with it. As long as it was regarded as just a somewhat simpler way to “save the appearances,” the Church was fine.

2. Heliocentrism careened into trouble with dogma when Galileo asserted that it wasn’t just a better way to predict positions, but was actually real. He pointed to his observations through the telescope to support that claim, saying that the universe necessarily had to be this way. As scripture understands that the Earth is stationary, this ran afoul of the doctrine of necessity: scripture can be reinterpreted in a more metaphorical way but only when necessary. The Pope, once a friend of Galileo, was once heard shouting at him “The blessed Lord will not be necessitated!”

3. So didn’t Galileo’s evidence point to the truth of heliocentrism? Well, sort of, maybe, yes and no. For one thing, everyone knew Galileo had a habit of embellishing the truth. And when church officials looked through his telescope, they discovered what a terrible lens maker Galileo was. His glass had flaws, bits of embedded crystal, sometimes it produced double images, and the field of view was so narrow that as soon as you got it pointed at something, the rotation of the Earth immediately carried it out of view again. You could make a plausible case that Galileo didn’t really see what he thought he saw.

### So have we now proven the universe is heliocentric?

No.

Remember Aristotle’s position that no number of special cases can ever prove a general result? He’s still right, and that is why you won’t ever hear the word “proof” come out of a scientist. The strongest you can say is that the evidence supports your theory.

And anyway, the universe is not heliocentric. Neither is the solar system.

***Discuss your results with your instructor at this point***

Now of course Copernicus did not have a good value for the size of the Earth’s orbit and neither did anyone else. Aristarchus had taken a crack at it using eclipses and the time between first and last quarter of the Moon. His value was big but not nearly big enough due to the uncertainty in when the Moon is exactly at the quarter phases. Eratosthenes also gave it a shot but he was either way off or sort of in the ballpark depending on which ancient report you believe (his original is lost) and which definition of the ancient distance unit the stadium you believe he used.

A value was not actually obtained until Giovanni Cassini (who was not an astrologer) and his friend Jean Richer (also not) did it in 1671. But Cassini had access to some information that Copernicus never had, information that was discovered by Johannes Kepler, who lived in between Copernicus and Cassini. He also had access to significantly better angle measurement tools.

So let’s look at Kepler (who was an astrologer) next.

## IV. Summary

Describe in a few sentences the most important things you learned about (a) solar system movements and (b) the scientific process from this activity.

***Discuss your results with your instructor at this point***

1. If you’re interested in a better picture of what happened and the variety of ideas over time, you could hardly do better than Robert Park’s history *The How and the Why* [↑](#footnote-ref-1)
2. Notably not Aristarchus. He was the first person to take a crack at measuring the sizes of things and, while he did not get actual numbers, he did show that the Sun was way larger than the Earth and it did not make sense to him that something that big should be going around something this small. He believed the Sun was at the center and the Earth went around it. For this reason, he was largely regarded as a weirdo. [↑](#footnote-ref-2)
3. If you happen to be a math major, you can think of this as a Fourier expansion of an ellipse. [↑](#footnote-ref-3)