Galileo and Changing Views of the Universe

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Introduction

Most of us are familiar with the fact that Galileo was brought to trial and censored by the church for promoting the view that the earth revolves around the sun. This trial is often viewed as a conflict between Christian faith and science. However, the situation was much more complicated than that. In 1962 Thomas Kuhn wrote a very influential book entitled **The Structure of Scientific Revolutions**. In this book he describes how historically science has not followed a straight line path of gradual improvement, but instead there have been normal periods where science operates under a structure of shared assumptions and approaches to problems called a paradigm that in due time is interrupted by a revolutionary paradigm shift. A paradigm shift represents a radically different way of thinking about the world. It usually involves more than the rejection of a single idea, but instead it involves changes in multiple interconnected ideas. Initially the new paradigm is vigorously resisted while support for the new paradigm is being developed. Eventually there follows a new normal period where the new paradigm prevails. Galileo was part of a major paradigm shift. Prior to the 16th century, the scientific view of the universe was based primarily on the ideas of Aristotle (384–322 B.C.) and the later refinements of these ideas by Ptolemy (c.85–165 A.D.). They assumed among other things that the earth was stationary and was the center of the universe. The sun, moon, and the other planets were assumed to revolve around the earth. They also believed that the moon and everything beyond were part of a perfect, unchanging region where all the stars and planets were composed of a special weightless material called aether, unlike anything found on earth. It is remarkable that this way of viewing the universe was commonly accepted for almost 2000 years. Although we now know that most of the ideas of Aristotle and Ptolemy about the universe we live in were wrong, there were very powerful common-sense arguments for believing them at the time. The first real challenge to the Aristotelian view was presented by Copernicus. Nicolas Copernicus (1473–1543) developed a model for the solar system in which the earth and the other planets orbited around the sun. Although the model he developed was as complicated as that of Ptolemy and was no more accurate, it did seem to provide better explanations of certain features. This stimulated other scientists to think about better ways of describing the heavens. Galileo was a supporter of the Copernican view and offered several pieces of evidence against the Aristotelian viewpoint. Using the recently invented telescope he observed such things as mountains on the moon, several moons orbiting Jupiter, sun spots, and phases of Venus. Although these observations were not sufficient to completely overthrow the current paradigm, they did present significant problems for the Aristotelian viewpoint. However, there still remained a number of common-sense objections to a sun-centered system such as

- Why don't we feel like we are moving?

- Why don't we feel a wind as we move through the air?
- Why don't objects fly off a rotating earth?
- What is powerful enough to move the earth and keep it moving?
- Why don't we observe stellar parallax if we orbit the sun?

These objections were eventually answered, but it took a new formulation of physics by Newton (1643–1727) and more accurate measurements to provide the answers. As you can imagine, Galileo's advocacy of the Copernican model met stiff resistance both from the academic community and the church. If anything, the resistance from the academic community was the stronger of the two. Galileo had a number of backers within the church community, but very few in the academic community. The resistance from the church stemmed from the fact that Thomas Aquinas (1225–1274) had incorporated many of Aristotle's views into a Christian theology that became part of official church doctrine. This theology was consistent with several passages in the Bible that seemed to support an earth-centered view. The church didn't object to a sun-centered model of the universe as long as it was treated as a computational tool and was not presented as representing reality. On the other hand, members of the academic community saw this paradigm shift as a threat to the cherished beliefs on which their careers were founded.

In this paper we will look at the reason's behind the long tenure of the Aristotelian viewpoint as well as the work of Copernicus, Galileo, Kepler, Brahe, and Newton that eventually lead to its downfall. We will also look at the trial of Galileo and some of the events that led up to it. Finally, we will see how the Christian church eventually modified its interpretation of certain passages of scripture that seemed to support a stationary earth. It was realized that the language used in these passages didn't have to be taken literally, but could be interpreted in a poetic or phenomenological manner. The paradigm shift brought about changes in both science and Christian theology. In both cases the changes were resisted initially but eventually converged toward a peaceful solution.

Aristotle(384–322 B.C.)

Aristotle was born in a small Greek colony in northern Greece called Stagira. His father was the personal physician to Philip of Macedon, the grandfather of Alexander the Great. Presumably, it was his father who taught him to take an interest in the details of natural life. At the age of eighteen, Aristotle became a student at the Academy of Plato. After Plato's death, Aristotle spent four years as a tutor of Alexander (later to become Alexander the Great). Later on, during his military conquests, Alexander helped to spread Greek culture (including Aristotle's work) to other regions. In 335 B.C. Aristotle returned to Athens and started his own school called the Lyceum. Aristotle was interested in almost everything—government, ethics, philosophy, science, etc. He pretty much invented modern logic. Although Aristotle had great admiration for Plato, he disagreed with his teacher on a number of things. One of these disagreements was on the nature of forms (ideals). Plato was searching for a certain and unchanging basis on which to base knowledge. Thus, he postulated an unchanging world of ideals or forms for which visible objects were merely an imperfect representation. For example, there is an ideal concept of a chair that is universal and applies to all chairs at all times. However, there are many different representations of a chair in the visible world. Central to the concept of forms was the idea of purpose. For example, the purpose of a chair was to provide a place to sit. To Plato these forms could only be approached through reason. Aristotle also believed in universals and ideals, but he didn't believe that they could be separated from the visible world. In fact, he believed that these ideals or forms could only be recognized by studying the real world of concrete objects. Aristotle used the word 'essence' for these ideals, and believed that every substance was a unity of essence and matter. Aristotle's primary scientific interest was in biology. He observed and cataloged a large number of plants and animals, and divided them into classes. He observed how living things developed. For example, an acorn always developed into an oak tree. Thus, he believed that the acorn had built into it an essence or purpose that was fully realized when it became an oak tree. He transferred this idea of essence to inanimate objects as well. He thought that all objects here on earth were made up of four basic elements—earth, water, air, and fire. He believed that the essence or goal of the earth element was to move toward the center of the universe which he took as the center of the earth. That is why heavy objects containing a lot of the earth element tend to fall toward the ground. The essence of water is also to move toward the center of the universe, but this nature is not as strong as it is for earth. Air and fire have a natural goal to rise above the earth. This natural essence is greater for fire than it is for air. There was one class of objects that didn't fit into this scheme, namely the stars and planets. They seemed always to be moving in a circular path at a uniform speed. Therefore, Aristotle divided the universe into two regions: the region consisting of the earth and everything in between the earth and the moon (sublunar region) and the region beyond the moon (the superlunar region). The sublunar region is composed of the four basic elements. The superlunar region is composed of a fifth weightless element called aether or quintessence. The nature of aether is to move in a circular path with a constant speed. It seems strange to us to assign purposes and goals to inanimate objects, but to Aristotle this was what caused objects to behave as they do. Instead of avoiding motion and change as Plato did with his world of unchangeable forms, Aristotle embraced change and sought out causes for change and motion. Aristotle considered two types of causes for motion. There is natural motion that is due to an object's built in essence and there is motion that is caused by an outside agent. He called motion produced by an external agent 'violent motion.' All motion in the sublunar region eventually stops. Violent motion stops when the external agent stops pushing or pulling. Natural motion stops when the object has reached its natural place or when it is prevented from doing so by another object, e.g. a falling rock stops when it hits the ground. Based largely on Aristotle's ideas a view of the physical universe was developed that was the dominant view from about 300 BC up into the sixteenth century. Here are some of the components of this view

1. The universe is eternal. It had no beginning and no foreseeable end.
2. The earth is spherical.
3. The earth is located at the center of the universe.
4. The earth is stationary, i.e., it doesn't rotate or revolve around any other object.
5. The stars, the moon, the planets, and the sun revolve around the Earth, completing a revolution about every 24 hours.
6. The sublunar region is composed of four basic elements: earth, water, air, and fire. This region is subject to change and decay.
7. The superlunar region is composed of a fifth element called aether whose natural motion is circular at a uniform rate. The superlunar region is perfect and unchangeable.
8. All motion in the sublunar region eventually stops.
9. An object that is stationary will remain stationary unless there is some source of motion.

You may be surprised that it was realized at this early date that the earth is spherical. However, there were several observations that led the ancient Greeks to this conclusion.

- The sun rises and sets at different times as you move in an east-west direction.
- The positions of constellations in the sky change as you move in a north-south direction. New constellations may come into view and others may disappear.
- As a ship approaches land the land appears to rise out of the sea. High points appear above the horizon first and later on the lower regions.

- During a lunar eclipse, the shadow of the earth on the moon appears circular.

The Greek's idea of a spherical earth spread to other regions, and by 800 A.D. it was rare to find any people group that believed in a flat earth.

There are a number of observations that led to the belief that the earth is stationary.

a. It doesn't feel like we are moving.

b. We don't feel the wind-like effects of the air as we move through it.

c. Dropped objects fall straight down. It was believed that if we were moving, then we would have moved ahead a certain distance as the object was falling and the object would land behind us.

d. The earth is very big and heavy, and there is no obvious source capable of moving it.

e. We don't observe stellar parallax (the change of relative positions of stars due to changes in the observer's position).

Although the reasons given for a stationary earth seemed very reasonable at the time, most of us today believe that the earth does move and that it revolves around the sun. However, you might ask yourself why you believe this. For most of us, it is because someone told us or because we read it in a book. It may surprise you that even today we don't have any direct observations that we revolve around the sun. As we will see, the reasons that this is the accepted viewpoint today are very subtle and not at all obvious.

The idea of the earth being the center is perfectly natural if the earth is stationary since all the heavenly bodies appear to revolve around the earth. Belief in the earth as the center was not motivated primarily by the belief that the center was a place of great importance, but was believed primarily on physical grounds. In fact, the superlunar region was considered to be the place of greatest perfection and importance. The earth was characterized by imperfection and decay.

The idea of parallax probably requires some explanation. If you hold up a piece of paper in front of you and hold up a finger in front of the paper, you will notice that your finger appears to move from one side of the paper to the other as you move your head from side to side. This phenomenon is called parallax and involves the apparent change of the relative positions of objects due to changes in position of the observer. If the earth were circling the sun, the relative position of stars should exhibit parallax when viewed from different positions in the orbit. Since none was observed, this was taken as evidence of a stationary earth. It turns out that parallax is real, but because the stars are so far away our instruments were not accurate enough to measure it until the year 1838 A.D. Stellar parallax is probably the best empirical evidence we have today that the earth revolves around the sun.

It can be calculated that the earth is revolving around the sun at about 70,000 mph and is rotating about its axis at about 1000 mph at the equator. Yet we don't feel like we are moving. The reason we don't feel the motion is that the earth, ourselves, and the atmosphere are moving together at a fairly constant speed. If we are traveling in a vehicle at a constant speed and there is very little vibration, we don't feel like we are moving. What we feel is change of motion (acceleration). The fact that we don't feel a strong wind is due to the fact that the atmosphere is by-and-large moving with the earth. There have been various reasons proposed for why the atmosphere moves with the earth. Gravity keeps the atmosphere from escaping from the earth and would tend to keep it moving along the earth's orbit around the sun. However, gravity doesn't force the atmosphere to rotate with the earth. This is thought to be due primarily to viscosity. Since the earth's surface is very uneven, the atmosphere near the surface is dragged along as the earth rotates. The viscosity of the atmospheric gases (even though small) eventually causes the rest of the atmosphere to follow along. There are of course winds that are due primarily to temperature variations. However these winds are very small compared to the winds that would be present if the atmosphere didn't move with the earth.

The reason that objects appear to drop straight down is that the velocity of the dropped object has two components—the downward velocity produced by gravity and the velocity in the direction of motion that it shares with us. The velocity it initially shares with us persists as the object falls, since there is no force to change it (the principal of inertia). Thus, the dropped object not only moves downward, but also moves forward just as we do. A true understanding of relative motion and inertia was not obtained until the 16th and 17th centuries (Galileo and Newton).

Everyone realizes that it takes considerable effort to move a heavy object such as a large rock. The earth was certainly a very large and heavy object, and there didn't appear to be any agent around powerful enough to move it and to keep it moving. The concept of inertia was not understood until the time of Galileo and Newton. Newton's laws imply that once an object is in motion it takes a force sufficient to overcome its inertia in order to bring it to a stop. The earth was set in motion during the creation of the solar system. The major force acting on the earth today is the gravitational attraction of the sun. This force causes the earth to speed up in certain parts of its orbit and to slow down in others, but it never acts in such a manner as to bring it to a halt. In fact it can be shown that the earth-sun system is periodic. As an aside, the idea of gravitational attraction itself is somewhat mysterious. How can an object exert a force on another object when there is no contact? Many thought that Newton was engaging in witchcraft when he first proposed the idea.

Although we now believe that most of Aristotle's beliefs concerning the solar system are false, they seemed to be very reasonable at the time. In fact these views were not seriously challenged until the 16th century.

Today we know that stars consist of hot gases and planets are composed of hard materials much like we have on earth. However, prior to the development of the telescope there was no reason to think that the lights seen in the sky were made of materials like those on the earth. The fact that the stars moved in a regular pattern year after year led to the idea that the superlunar region represented perfection. The motion of the stars was very different from observed motion on the earth which always eventually comes to a halt. Thus, these ideas of Aristotle seemed reasonable prior to the time of Galileo.

Movement of the Sun, Moon, Stars, and Planets

From early times man has had an interest in the objects he saw in the heavens. Great significance was often attached to the ways these objects seemed to move. In this section we will look at how the stars and planets appear to move as viewed from the earth. We have mentioned that each star follows a circular path across the sky that repeats about every 24 hours. However, the stars move together so that their relative positions remain unchanged. For this reason they are often referred to as the fixed stars. The star Polaris appears to be fixed to viewers in the northern hemisphere and there are polar stars that appear to be fixed to viewers in the Southern hemisphere Thus, the movement of the stars is exactly what would be expected if all the stars were located on a giant rotating sphere whose axis passes through Polaris and the southern polar stars and which makes a complete rotation every 24 hours. The fixed stars do not appear to change in brightness.

The Sun appears to follow a circular path each day, rising in the east and setting in the west. However, the sun's position relative to the fixed stars changes slightly each day (about 1° per day). This daily movement is in an eastward direction relative to the fixed stars and the sun completes a cycle through the stars in a year. The path of the sun through the fixed stars lies in a plane that is inclined about 23.5° to the plane of the equator. The sun passes through different constellations at different times of the year, and this is what gave rise to the signs of the zodiac. Of course, the position of the sun relative to the fixed stars can only be observed for a short time before sunrise and after sunset.

The moon, like the sun, moves daily relative to the fixed stars, but its motion is faster. Its path is inclined about 5° to that of the sun and it completes a cycle in about 27.3 days. However, since the sun has moved during the moon's cycle, it takes a short time for the moon to realign itself with the sun. Thus, the time between full moons is about 29.5 days. The phases of the moon are due to the fact that different portions of the illuminated half of the moon are visible to an observer on the earth when the moon is in different parts of its orbit.

There were five planets (not counting the sun and moon) that were known to ancient astronomers—Mercury, Venus, Mars, Jupiter, and Saturn. On any given night a planet (when it is visible) moves just like one of the fixed stars. You may have heard that stars flicker and planets don't. There is some truth in this, but it is difficult to identify planets on this basis alone. The main thing that distinguishes planets from stars is that on successive nights they, like the sun and moon, move slowly eastward relative to the fixed stars. The paths of the planets lie within 8° of the path of the sun; so they pass through the same constellations. Each of the planets at certain times exhibits retrograde motion in which it stops and moves for a while in the reverse direction before stopping again and then resuming its eastward motion. The planets Mercury and Venus never appear very far from the sun. Mercury is always within 28° of the sun and Venus is always within 46° of the sun. Thus, Mercury and Venus are only visible in the hours just before sunrise and the hours just after sunset. As the sun makes its yearly journey, Mercury and Venus move back and forth across the sun. Unlike the stars, the planets do change brightness. They are brightest during their retrograde motion. This complicated movement of the planets is what makes modeling their movement versus time difficult.

Ptolemy (c.85–165 A.D.)

Aristotle's view of the solar system was greatly expanded by Claudius Ptolemy. Not much is known about Ptolemy's life except that he was a mathematician and astronomer that lived in Alexandria, Egypt during the last part of the first century A.D. into the second century A.D. At that time Egypt was a Roman province. His famous work was the Almagest in which he layed out a model for the motion of the planets that was based on the ideas of Aristotle. Each planet was modeled separately. To handle the retrograde movement of the planets he introduced epicycles. An epicycle is a smaller circle whose center moves in a circular orbit around the earth. Like Aristotle, Ptolemy took the earth as the center of the universe. As such, the earth was the center of the sphere containing the fixed stars. However, the earth was not taken as the center of a planet's orbit. A planet moved at a constant angular velocity around an epicycle whose center moved at a constant angular velocity around a larger circle whose center was displaced somewhat from the earth. Epicycles were introduced primarily to handle retrograde motion. It was observed that planets moved faster in some parts of their orbit than in others. To handle this nonuniform motion, Ptolemy introduced another point called the 'equant.' It was assumed that the angular velocity relative to this point was constant. This produced a nonuniform angular velocity relative to the center. Figure 1 shows the basic parts of Ptolemy's model of planetary motion.

Since Mercury and Venus always appeared close to the sun, Ptolemy assumed that the centers of their epicycles lay on the line connecting the earth and the sun and that they rotated around the earth at the same rate as the sun does. This is illustrated in Figure 2.

The retrograde motion of the outer planets (Mars, Jupiter, and Saturn) always occurs in the night sky and the planet is always brightest during this retrograde motion. To accomplish this Ptolemy required that the arrow from the center of a planet's epicycle to the planet always be parallel to the arrow from the earth to the sun. This configuration is shown in Figure 3.

Using models such as this, Ptolemy was able to predict the motion of the planets fairly accurately. Sometimes he needed to introduce epicycles riding on other epicycles to get the desired accuracy. Ptolemy's planetary model was the generally accepted model for planetary motion up into the 16^{th} century. It is not known how Ptolemy viewed his planetary model. Did he think that his model represented reality, or was it merely a computational tool for producing results that agree with observation. Even today Scientists often disagree on whether certain theories really represent reality or not. At the time of Galileo the church didn't object to a sun-centered universe as a computational tool, but it did object to claims that it represented reality.

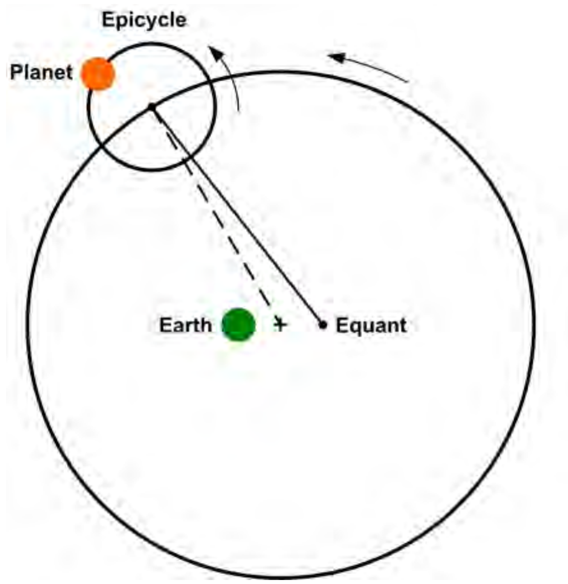

Figure 1: The planetary model of Ptolemy

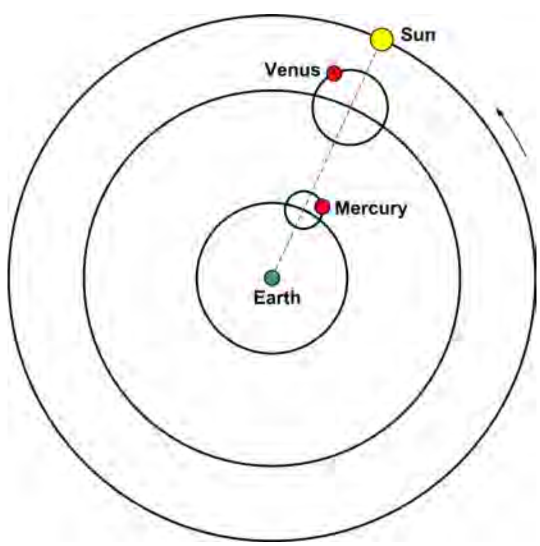

Figure 2: Mercury and Venus according to Ptolemy's model.

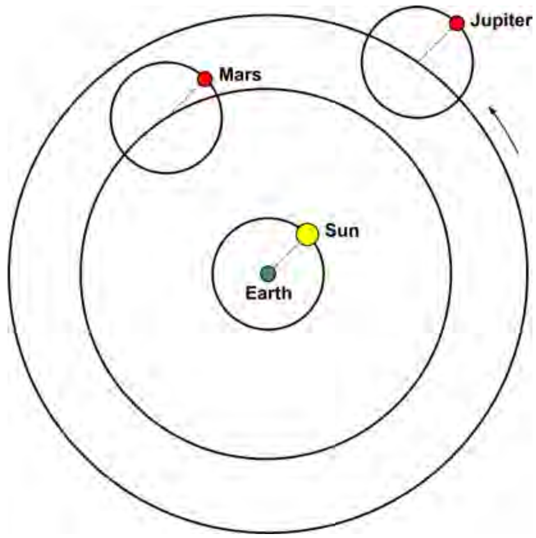

Figure 3: Outer Planets according to Ptolemy's model.

There were two aspects of Ptolemy's models that persisted in the sun-centered models of Copernicus. These were the requirements that all motions be circular and at a uniform speed. These requirements were not dropped until Kepler developed his laws of planetary motion.

Copernicus (1473–1543)

Nicolas Copernicus was a Polish mathematician and astronomer who served as Canon (an administrative position) for the church in Frauenberg. In the early 1500s he developed a sun-centered model that was the first real challenge to the long accepted model of Aristotle and Ptolemy. His major work was called **Revolutions of the Celestial Spheres** which was published just before his death in 1543. A Lutheran Minister Andrew Osiander handled the publication and inserted a preface without Copernicus' knowledge. In this preface he wrote that Copernicus was merely offering a hypothesis, not a true account of the workings of the heavens. Although this clearly did not represent Copernicus' viewpoint, it probably protected this work from close scrutiny by the church. Copernicus' model offered the advantages that it didn't need epicycles in order to produce retrograde movement and it didn't need an equant point in order to produce non-uniform motion. However, epicycles were added in order to obtain accurate predictions. The accuracy of his model was good, but it was no better than Ptolemy's model. As far as complexity, Copernicus' model was at least as complex as Ptolemy's model. Figure 4 shows Copernicus' model for Mars. The models for Jupiter and Saturn were similar to that of Mars, but the models for Venus and Mercury were even more complex.

In this model Mars follows a circular path around the point A. The point A follows a circular path around the point B. The point B also moves, but always stays in the same position relative to the point C. The point C is the center of the circular path followed by the Earth (not shown). C follows a circular path around the point D which in turn follows a circular path around the Sun. As with Ptolemy's model, Copernicus assumed that the points moved around their circular paths at a constant speed. In the years that followed, a number of astronomers used Copernicus' model to make predictions. However, most viewed his model as a computational tool and not a representation of reality.

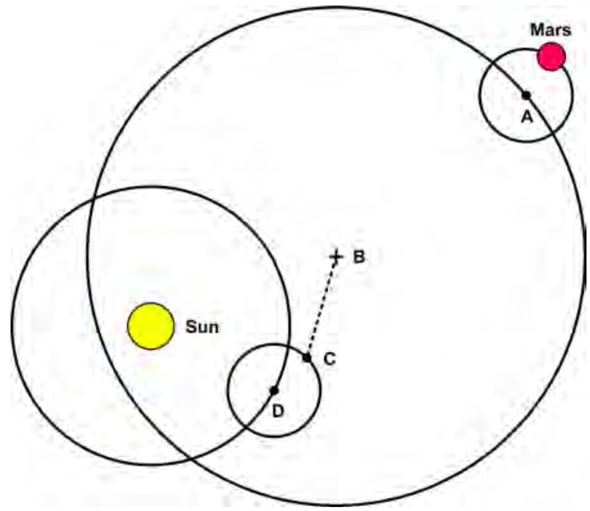

Figure 4: Copernican model of Mars

Problems Emerge for Aristotelian Viewpoint

A working telescope was first unveiled in the Netherlands in 1608. Initially it was used for military applications. In 1609 Galileo began using the telescope for astronomical observations. He refined the instrument and eventually achieved a magnification of 30x. His observations with the telescope challenged many of Aristotle's assumptions. His observations of the moon revealed an uneven (mountainous) surface much as we have on the earth. He also observed sun spots by projecting a telescopic image onto a piece of paper. These observations challenged the assumed perfection of the superlunar region. He also observed objects he correctly identified as moons revolving around the planet Jupiter. This challenged the view that everything revolved around a stationary earth. Here was an example of objects revolving around another object that was itself moving. He also observed that the planet Venus went through a complete set of phases like those of the moon. This was consistent with the sun-centered model of Copernicus (1473–1543), but was not consistent with Ptolemy's model. In Ptolemy's model Mercury and Venus had orbits between the earth and the sun. Since they always appear close to the sun, the centers of their epicycles must revolve around the earth at the same rate as the sun does. Thus, Ptolemy's model would never show a wide range of phases. There is always a significane portion of the dark side of Venus facing the earth. You can see this from Figure 5.

Figure 6 shows the phases of Venus in the Copernican model (without epicycles). Here an observer on the earth will see a wide range of phases. Galileo's observations were repeated by Jesuit astronomers, and they confirmed what he saw.

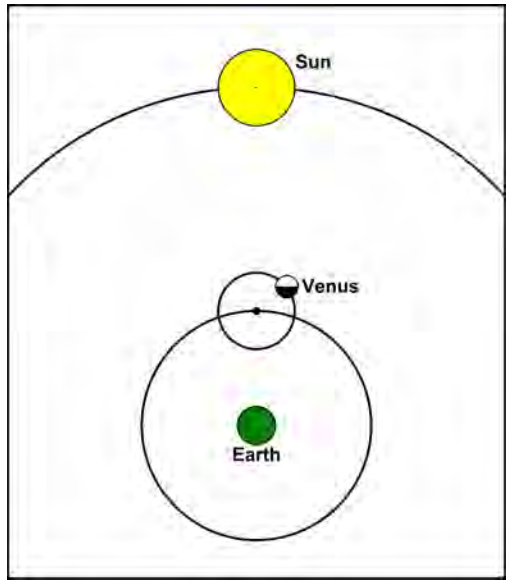

Figure 5: Venus phases in Ptolemy's model.

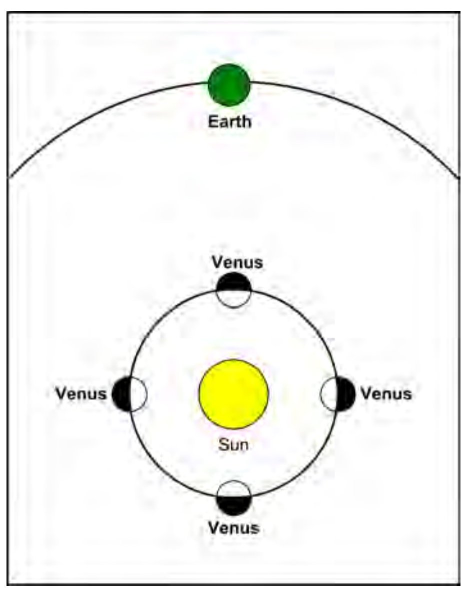

Figure 6: Venus phases in Copernican model

Galileo viewed his observations as a confirmation of the sun-centered Copernican model. Although his observations did pose a serious threat to the model of Aristotle and Ptolemy, there was another earth-centered model that produced accurate results and was also consistent with Galileo's observations. This was the model proposed by the Danish astronomer Tycho Brahe.

Tycho Brahe (1546–1601)

Tycho Brahe was a Danish astronomer who was well know for his accurate measurements of the heavens. He saw the benefits of both the Copernicus model and Ptolemy's model. He proposed a model that was a combination of the two. He assumed that the earth was stationary and was located at the center of the universe. The sun and the moon revolved around the earth. The other five planets revolved around the sun. Figure 7 shows his model (without epicycles). It is not obvious, but it

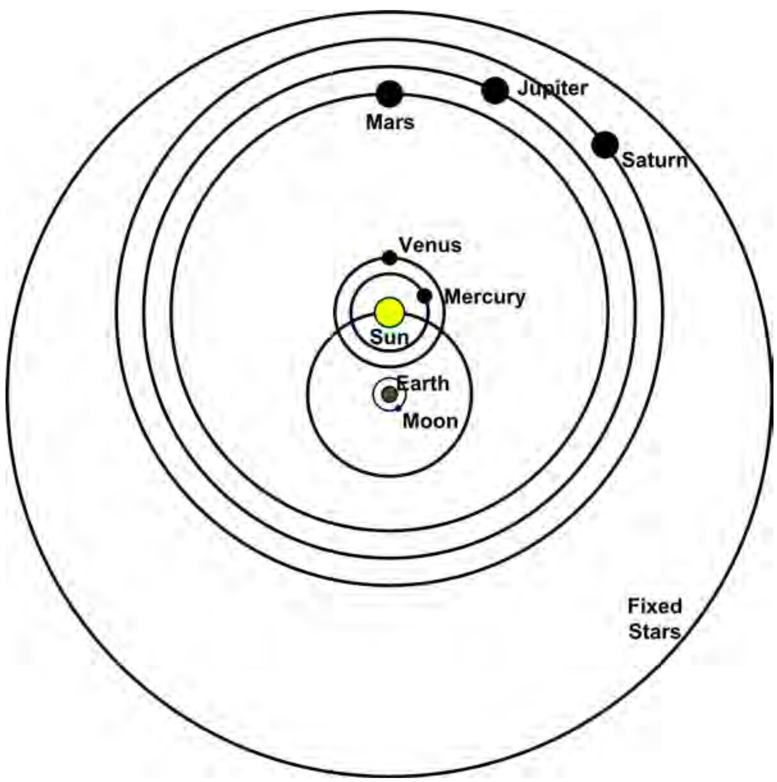

Figure 7: Planetary model of Tycho Brahe

can be shown that Tycho Brahe's model is mathematically equivalent to the Copernicus model. Therefore, they have the same accuracy. The model of Tycho Brahe had the advantage of being consistent with Ptolemy's intuitive arguments for a stationary earth. Thus, at this point in history, belief in an earth-centered universe was still a very rational position.

The Trial of Galileo

There were a number of factors unrelated to science that contributed to Galileo's condemnation by the church. Historically the church had been fairly tolerant towards scientific challenges, being willing to alter interpretations of scripture when it was deemed necessary. However, the Catholic church at this time was battling the rise of Protestantism and one of the main points of contention was who had the authority to interpret scripture. The Catholic church maintained that only official church theologians had this authority. Galileo had suggested that a moving earth did not contradict the scriptures since the Bible often uses metaphors when speaking of natural events. Therefore, they felt that it was dangerous at this time to allow a layman such as Galileo to dictate how certain passages of scripture should be interpreted. This may be one of the reasons that the church took a tough stand when dealing with Galileo. In addition, Galileo made a number of political blunders. Initially the Jesuits had been strong supporters of Galileo. They had confirmed his observations with the telescope and had enthusiastically endorsed him to the officials in Rome. . However, starting in 1611, Galileo began studying the motion of sunspots (small dark spots on the surface of the sun). These were observed independently by a prominent Jesuit astronomer, Christopher Scheiner. Scheiner believed that these spots were small dark objects orbiting the sun at some distance. Galileo believed that the evidence pointed to the spots being on the surface of the sun. Galileo published his results in 1613 and asserted his priority of discovery. This angered Scheiner.

In 1618 three new comets wee observed. Orazio Grassi, a prominent Jesuit mathematician, wrote a book using the pseudonym Lothario Sarsi that discussed the comets. In this book he argued that comets followed paths close to those of planets, but had shorter lifetimes. Galileo knew from his observations that comets moved in a straight line most of the time. In a 1623 publication, The Assayer, Galileo offered support for his position and made the following degrading remark concerning Sarsi

> *In Sarsi I seem to discern the firm belief that in philosophising one must support oneself on the opinion of some celebrated author, as if our minds ought to remain completely sterile and barren unless wedded to the reasoning of someone else. Possibly he thinks that philosophy is a book of fiction by some author, like the Iliad or Orlando Furioso—productions in which the least important thing is whether what is written in them is true. Well, Sarsi, that is not how things are. Philosophy is written in this grand book the universe, which stands continually open to our gaze. But the book cannot be understood unless one first learns to comprehend the language and to read the alphabet in which it is composed. It is written in the language of mathematics,*

and its characters are triangles, circles, and other geometric figures, without which it is humanly impossible to understand a single word of it; without these one wanders about in a dark labyrinth.

This attack on one of their own further angered the Jesuits. Galileo, in his writings, would often seek to destroy his opponents as well as their arguments.

As was mentioned previously in the introduction, Galileo's biggest enemies were from the academic community. Aristotle was treated as a hero in academic circles, and Galileo's attacks on Aristotelianism were met with considerable resistance. In addition Galileo chose to publish in Italian, the language of the people, rather than in Latin as was the norm in academic publications. It is probable that some of the academics used their influence to incite the church against Galileo.

The sun-centered model of Copernicus received little attention by the church in the years following its release. This was probably due to the fact that most viewed it as a computational device and not as a representation of reality. However, the attention paid to it by Galileo caused some concern. The Copernican system was condemned by the church in 1616. The Pope asked Cardinal Bellarmine to convey news of this condemnation to Galileo. Bellarmine was the chief theologian of the church. Galileo met with Bellarmine and was given an affidavit that stated that Galileo was to no longer to hold or defend the propositions that the earth moves and the sun doesn't. Bellarmine himself didn't seem to be completely closed-minded on the subject. In a letter to a friend he once stated

Third, I say that if there were a true demonstration that the sun is at the center of the world and the earth is in the third heaven, and that the sun does not circle the earth but the earth circles the sun, then one would have to proceed with great care in explaining the scriptures that appear contrary, and say rather that we do not understand them than what is demonstrated is false. But I will not believe such a demonstration, until it is shown me.

This doesn't sound like a mindless rejection of the Copernican system. Unknown to Galileo, an unsigned memo was given to the Pope that supposedly came from the meeting with Cardinal Bellarmine. It stated that Galileo was no longer to hold, defend, or teach the aforementioned propositions. The inclusion of the word **teach** was important since it meant that Galileo could not even describe the Copernican system. This memo would show up later in the trial of Galileo. It is possible that this unsigned memo was produced by some of Galileo's enemies.

In 1623 Mafeo Barberini became Pope Urban VIII. Barberini was an admirer of Galileo and once had confided to him his pet theory that even though the universe may be most simply understood by thinking the sun at rest, God could have arranged it that way, but with the earth at rest. With his friend and admirer now the Pope, Galileo felt more confident in arguing for the Copernican system. In 1632 he published a document in which he disguised his position by presenting his arguments as part of a three person dialogue. It was titled **Dialogue Concerning the Two Chief Systems of the World—Ptolemaic and Copernican**. One of the participants in this dialogue was named Salviati. He was the spokesman for Galileo and presented brilliantly the case for Copernicanism. The second participant was named Simplicio. He represented an Aristotelian professor who was portrayed as ill-informed and not very bright. The name Simplicio is very close to the Italian word for simpleton. The third participant was named Sagredo. He represented an open-minded unbiased observer. Towards the end of the dialogue Galileo made the mistake of putting the statement of the Pope's pet theory in the mouth of Simplicio, the simpleton in this dialogue. It is unlikely that Galileo was trying to ridicule the Pope, but he may have thought that no one would notice. However, Galileo's enemies picked this up quickly and convinced the Pope that he was being ridiculed. The Pope was not amused. In August of 1632 the Inquisition in Rome issued an order to stop the publication of the Dialogue, and Galileo was ordered to stand trial. The trial was not about the scientific merits of Galileo's views, but was about whether Galileo had disobeyed an official order. The unsigned memo was issued as evidence, but Galileo denied ever receiving a copy. Three officials reviewed the Dialogue and agreed that it did advocate Copernicanism. In an unusual move, it was suggested that Galileo could get off with a lighter sentence if he would admit some wrongdoing. He agreed to remove any parts the **Dialogue** that seemed to advocate Copernicanism and he admitted that he had gone too far in some of his arguments. He was sentenced to house arrest for the rest of his life, most of which was spent in his large villa near Florence. Three of the ten Cardinals involved in the inquisition did not sign the verdict. In the few years that remained of his life he made a number of important contributions to mechanics. Certainly the trial of Galileo was an unfortunate event that involved mistakes by both the Catholic church and by Galileo. However, to view this as a battle between science and Christianity is much too simple. There were a number of other factors involved. Science was undergoing a major paradigm shift and the church was facing significant opposition from the Protestant movement. Galileo shares some of the blame for the way he treated those who disagreed with him. It should also be noted that Galileo himself was a committed Christian before the trial and remained one afterwards.

The paradigm shift in science forced Christian theologians to reexamine verses that seemed to support a stationary earth. Today these verses are viewed differently. For example, the verse

> *Tremble before him all the earth! The world is firmly established; it cannot be moved.*
> 1 Chronicles 16:30

is seen as a poetic or metaphoric way of describing the stability of God's creation. Other verses such as

> *The sun rises and the sun sets, and hurries back to where it rises* Ecclesiastes 1:5

are seen as using phenomenological language. Certainly, the purpose of these verses was not to advocate some astronomical theory. The reinterpretation of these scriptures did nor affect any major Christian doctrine.

Some Final Notes

The model we use today is not the one introduced by Copernicus, but is essentially the one introduced later by Johannes Kepler (1571–1630). Kepler was a protege of Tycho Brahe and used Tycho's measurements to arrive at his model. One of the first things that Kepler did was to actually plot the motion of Mars as predicted by the Ptolemaic model. This motion is shown in Figure 8.

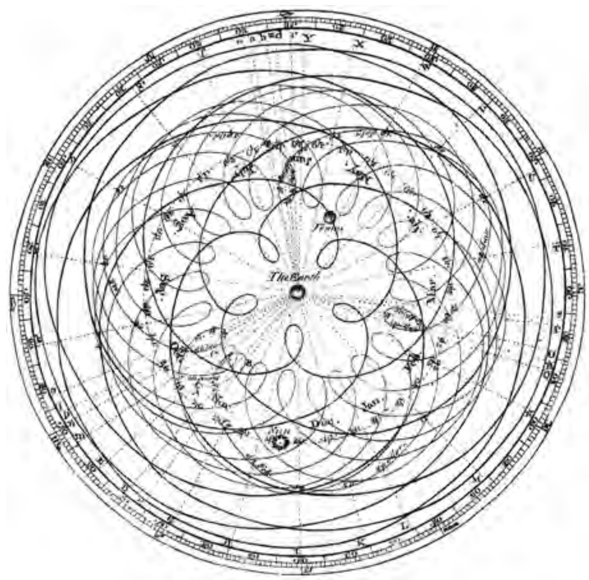

Figure 8: Plot of Mars orbit as predicted by Ptolemaic model. Taken from Astrnomia nova, chapter 1 (1609)

Kepler found it hard to believe that Mars would follow such a strange path with all the loops. He was attracted to the Copernican model, but he was not satisfied with the accuracy of its results. He finally arrived at a model based on the following three laws.

a. Kepler's First Law: A planet moves in a plane along an elliptical orbit with the sun at one focus.

b. Kepler's Second Law: The position vector from the sun to a planet sweeps out area at a constant rate.

c. Kepler's Third Law: The square of the period of a planet around the sun is proportional to the cube of the semi-major axis length.

These laws are an amazing achievement. Kepler was able to give up the long standing ideas of circular orbits and uniform speed. His laws were not derived from some theory, but were obtained by carefully examining empirical data. This was the first model that didn't require epicycles to produce accurate results. It should be noted that Kepler and Galileo were contemporaries and corresponded frequently. Although Galileo was familiar with Kepler's work, he refused to give up the idea of circular orbits. Kepler's laws were later derived by Newton from his laws of motion and his law of universal gravitation. The success of Newton's laws in many areas of mechanics added additional support to Kepler's model. The derivation of Kepler's laws from Newton's laws is contained in the Appendix. The final nail in the coffin of the earth-centered view was the measurement of stellar parallax. In 1838 Friedrich Bessel made the first successful parallax measurement, for the star 61 Cygni, using a Fraunhofer heliometer at Königsberg Observatory.

Appendix A Kepler's Laws Derived from Newton's Laws

In this appendix we will derive Kepler's laws from Newton's laws of motion and his law of universal gravitation.

Kepler's laws Below are the three laws that were derived empirically by Kepler.

- Kepler's First Law: A planet moves in a plane along an elliptical orbit with the sun at one focus.
- Kepler's Second Law: The position vector from the sun to a planet sweeps out area at a constant rate.
- Kepler's Third Law: The square of the period of a planet around the sun is proportional to the cube of the semi-major axis length.

Mathematical preliminaries Consider a Cartesian coordinate system with the sun at the origin. Let (x, y, z) denote the position of a planet. Clearly x, y, and z are functions of the time t. We define the position vector $\boldsymbol{r}$, the velocity vector $\boldsymbol{v}$, and the acceleration vector $\boldsymbol{a}$ by

$$\boldsymbol{r} = x\boldsymbol{i} + y\boldsymbol{j} + z\boldsymbol{k}, \qquad \boldsymbol{v} = \dot{x}\boldsymbol{i} + \dot{y}\boldsymbol{j} + \dot{z}\boldsymbol{k}, \qquad \boldsymbol{a} = \ddot{x}\boldsymbol{i} + \ddot{y}\boldsymbol{j} + \ddot{z}\boldsymbol{k}$$

Here the dots represent differentiation with respect to time and $\boldsymbol{i}$, $\boldsymbol{j}$, $\boldsymbol{k}$ are the unit vectors in the x, y, z directions respectively. Newton's law of motion can be written

$$\boldsymbol{F} = m\boldsymbol{a} \tag{1}$$

where m is the mass of the planet and $\boldsymbol{F}$ is the force on the planet. Let $\hat{\boldsymbol{r}}$ be a unit vector in the $\boldsymbol{r}$ direction. Then Newton's law of gravitation applied to the earth and sun is given by

$$\boldsymbol{F} = -\frac{GMm}{r^2}\hat{\boldsymbol{r}} = -\frac{GMm}{r^3}\boldsymbol{r} \tag{2}$$

where G is a constant, M is the mass of the sun, and r is the magnitude of $\boldsymbol{r}$. Combining equations (1) and (2), we get

$$\boldsymbol{a} = \ddot{\boldsymbol{r}} = -\frac{GM}{r^3}\boldsymbol{r} \tag{3}$$

Planet moves in a plane By the product rule for differentiation

$$\frac{d}{dt}(\boldsymbol{r} \times \boldsymbol{v}) = \boldsymbol{v} \times \boldsymbol{v} + \boldsymbol{r} \times \boldsymbol{a} = 0$$

since $\boldsymbol{a}$ is in the same direction as $\boldsymbol{r}$ by equation (3). Here the symbol $\times$ represents the vector cross-product. Thus, the vector

$$\boldsymbol{h} = \boldsymbol{r} \times \boldsymbol{v}$$

is a constant. It follows that $\boldsymbol{r}$ and $\boldsymbol{v}$ lie in the plane orthogonal to $\boldsymbol{h}$. We will choose our coordinate system so that $\boldsymbol{k}$ is in the direction $\boldsymbol{h}$. Thus,

$$\boldsymbol{h} = \boldsymbol{r} \times \boldsymbol{v} = h\boldsymbol{k} \qquad \text{where } h > 0. \tag{4}$$

Kepler's second law Figure 9 shows the area swept out by the position vector in a small increment of time. $\triangle\theta$ is the small change of angle. The area OAB is approximately equal to the area

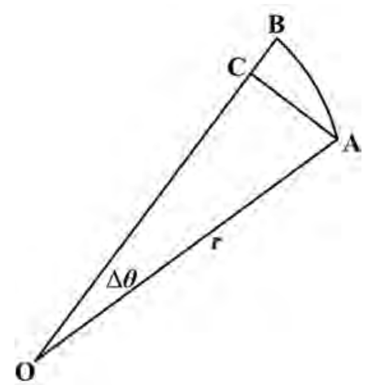

Figure 9: Area swept out during small time increment

of the right triangle OAC for small $\triangle\theta$. Since the length of the line AC is approximately $r\triangle\theta$ and the length of the line OC is approximately r, we have

$$\triangle A \doteq \tfrac{1}{2}r^2\triangle\theta.$$

Letting the time increment approach zero, we see that

$$\dot{A} = \tfrac{1}{2}r^2\dot{\theta}. \tag{5}$$

Since the planet moves in the xy plane, we have

$$\boldsymbol{r} = x\boldsymbol{i} + y\boldsymbol{j} = r\cos\theta\boldsymbol{i} + r\sin\theta\boldsymbol{j} \tag{6}$$

where the polar coordinates r and θ are functions of t. The time derivative of $\boldsymbol{r}$ is given by

$$\boldsymbol{v} = (\dot{r}\cos\theta - r\sin\theta\,\dot{\theta})\boldsymbol{i} + (\dot{r}\sin\theta + r\cos\theta\,\dot{\theta})\boldsymbol{j}. \tag{7}$$

Substituting equations (6) and (7) into equation (4), we obtain

$$h = r\cos\theta(\dot{r}\cos\theta + r\sin\theta\,\dot{\theta}) - r\sin\theta(\dot{r}\cos\theta - r\sin\theta\,\dot{\theta}) = r^2\dot{\theta}. \tag{8}$$

Here we have used the fact that $\boldsymbol{i} \times \boldsymbol{j} = \boldsymbol{k}$ and $\boldsymbol{j} \times \boldsymbol{i} = -\boldsymbol{k}$. It follows from equations (5) and (8) that

$$\dot{A} = \tfrac{1}{2}r^2\dot{\theta} = h/2 = \text{constant}.$$

This is Kepler's second law.

Definition and properties of an ellipse Before we look at the derivation of Kepler's first law, we need to define what we mean by an ellipse, and look at some of its properties. One common way of drawing an ellipse is to pin the two ends of a string, place a pencil in the loop, and trace a curve while keeping the string taught. Clearly the resulting curve has the property that the sum of the distances from any point on the curve to the two fixed points is a constant (the length of the string). The resulting curve is called an ellipse and the two fixed points are called the foci of the ellipse. Figure 10 shows an ellipse in which the foci are at $(-c, 0)$ and $(c, 0)$, and $2a$ corresponds to the length of the string. The construction of the ellipse can be represented mathematically as

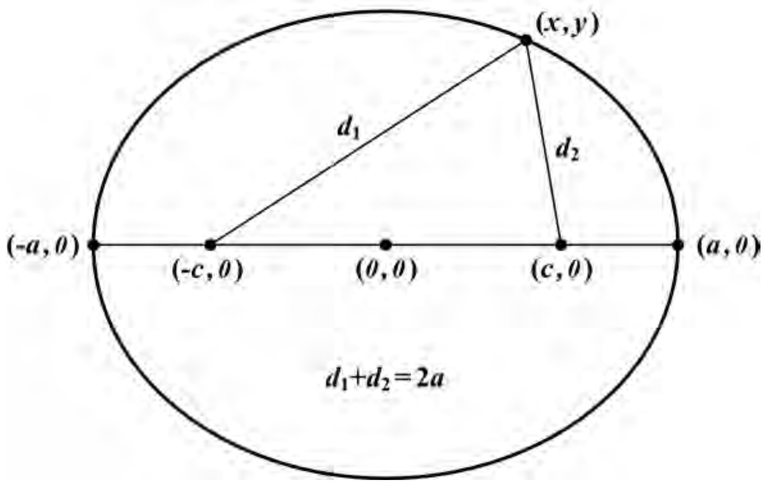

Figure 10: Drawing of an ellipse

follows

$$\sqrt{(x+c)^2+y^2}+\sqrt{(x-c)^2+y^2}=2a \qquad \text{where } a>c>0 \tag{9}$$

This equation can be rearranged as follows

$$\sqrt{(x+c)^2+y^2}=2a-\sqrt{(x-c)^2+y^2}.$$

Squaring both sides, we get

$$(x+c)^2+y^2=4a^2-4a\sqrt{(x-c)^2+y^2}+(x-c)^2+y^2.$$

Solving for the square root term, we obtain

$$\sqrt{(x-c)^2+y^2}=\frac{1}{4a}[4a^2+(x-c)^2-(x+c)^2]=a-\frac{c}{a}x.$$

Squaring again, we obtain

$$x^2-2cx+c^2+y^2=a^2-2cx+\frac{c^2}{a^2}x^2$$

or equivalently

$$(1-\frac{c^2}{a^2})+y^2=(a^2-c^2)\frac{x^2}{a^2}+y^2=a^2-c^2.$$

Dividing through by $a^2 - c^2$, we obtain

$$\frac{x^2}{a^2} + \frac{y^2}{a^2 - c^2} = 1. \tag{10}$$

We define the *eccentricity* e of the ellipse by $e = c/a$. We also define b by

$$b = a\sqrt{1 - e^2} = \sqrt{a^2 - c^2} \tag{11}$$

Thus, equation (10) can be written in the standard form

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1.$$

This is the form that is usually specified for an ellipse. It is easy to see that a is one-half the length of the ellipse's major axis and b is one-half the length of the ellipse's minor axis.

An ellipse also has a simple form in polar coordinates if we take our origin to be one of the foci. This situation is pictured in Figure 11. Using the definition of an ellipse in terms of the sum of the

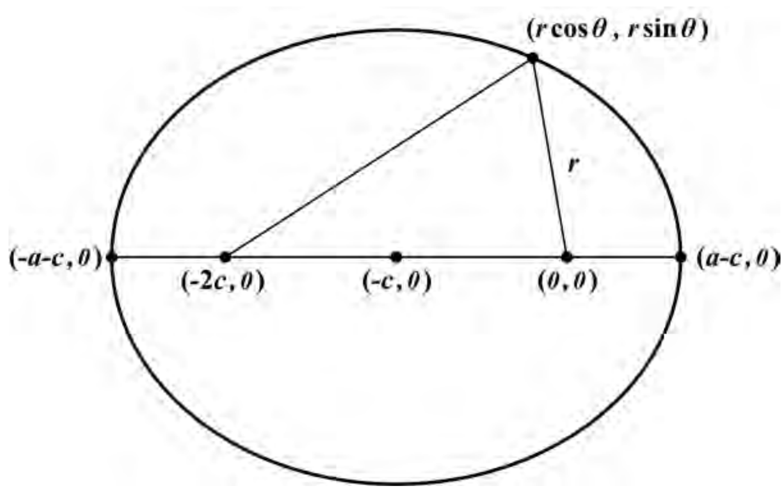

Figure 11: An ellipse in polar coordinates

distances from the two foci being constant, we can write

$$r + \sqrt{(r\cos\theta + 2c)^2 + r^2\sin^2\theta} = 2a. \tag{12}$$

Solving for the square root term and expanding the square terms, we get

$$\sqrt{r^2 + 4rc\cos\theta + 4c^2} = 2a - r.$$

Squaring this equation gives

$$r^2 + 4rc\cos\theta + 4c^2 = 4a^2 - 4ar + r^2$$

or equivalently

$$(a + c\cos\theta)r = a^2 - c^2.$$

Solving for r, we obtain

$$r = \frac{a^2 - c^2}{a + c\cos\theta} = \frac{a^2(1 - \frac{c^2}{a^2})}{a(1 + \frac{c}{a}\cos\theta)} = \frac{a(1 - e^2)}{1 + e\cos\theta} = \frac{k}{1 + e\cos\theta} \tag{13}$$

where $k = a(1-e^2)$. Equation (13) is the desired representation of the ellipse in polar coordinates.

We can also derive our original definition of an ellipse from the polar form. Suppose r and θ satisfy

$$r = \frac{k}{1 + e\cos\theta} \qquad \text{where } k > 0 \text{ and } 0 < e < 1. \tag{14}$$

We define a and c by

$$a = \frac{k}{1 - e^2} = \frac{k}{(1-e)(1+e)} \qquad \text{and} \qquad c = ae. \tag{15}$$

It follows from equation (14) that r has a maximum value of $\frac{k}{1-e}$ at $\theta = \pi$. Thus,

$$r \leq \frac{k}{1-e} = a(1+e) < 2a.$$

Equation (14) can be rearranged as follows

$$(1 + e\cos\theta)r = k = a(1 - e^2).$$

Since $e = c/a$, this equation can be written

$$\Big(1 + \frac{c}{a}\cos\theta\Big)r = a\Big(1 - \frac{c^2}{a^2}\Big) = \frac{a^2 - c^2}{a}.$$

Multiplying both sides by a, we obtain

$$(a + c\cos\theta)r = a^2 - c^2.$$

Multiplying this equation by 4 and adding $r^2 = (\sin^2\theta + \cos^2\theta)r^2$ to both sides, we obtain

$$(\cos^2\theta + \sin^2\theta)r^2 + 4ar + 4cr\cos\theta = 4a^2 - 4c^2 + r^2.$$

This equation can be rearranged as

$$r^2\cos^2\theta + 4cr\cos\theta + 4c^2 + r^2\sin^2\theta = r^2 - 4ar + 4a^2.$$

or equivalently

$$(r\cos\theta + 2c)^2 + r^2\sin^2\theta = (2a - r)^2.$$

Taking the square root of both sides, we obtain

$$r + \sqrt{(r\cos\theta + 2c)^2 + r^2\sin^2\theta} = 2a$$

which is the defining equation for the ellipse pictured in Figure 11 [see equation (12)]. Thus, equation (14) defines an ellipse with the origin at one focus. Let $b = a\sqrt{1 - e^2}$. Then it follows from equation (15) that

$$b = \frac{k}{\sqrt{1 - e^2}} \tag{16}$$

Hamilton's Theorem In this section we will show that the velocity vector $\boldsymbol{v}$ moves on a circle. Since $r = |\boldsymbol{r}|$, equation (3) can be written

$$\dot{\boldsymbol{v}} = \boldsymbol{a} = -\frac{GM}{r^2}(\cos\theta\,\boldsymbol{i} + \sin\theta\,\boldsymbol{j}). \tag{17}$$

Combining equations (8) and (17), we obtain

$$\dot{\boldsymbol{v}} = -\frac{GM}{h}\,\dot{\theta}\,(\cos\theta\,\boldsymbol{i} + \sin\theta\,\boldsymbol{j}). \tag{18}$$

By the chain rule for differentiation

$$\dot{\boldsymbol{v}} = \frac{d\boldsymbol{v}}{d\theta}\,\dot{\theta}. \tag{19}$$

It follows from equations (18) and (19) that

$$\frac{d\boldsymbol{v}}{d\theta} = -\frac{GM}{h}(\cos\theta\,\boldsymbol{i} + \sin\theta\,\boldsymbol{j}).$$

Integrating this equation, we obtain

$$\boldsymbol{v} = \frac{GM}{h}(-\sin\theta\,\boldsymbol{i} + \cos\theta\,\boldsymbol{j}) + \boldsymbol{v}_0 \tag{20}$$

where $\boldsymbol{v}_0$ is a constant. It follows that $|\boldsymbol{v} - \boldsymbol{v}_0| = GM/h$, i.e., $\boldsymbol{v}$ moves on the circle centered at $\boldsymbol{v}_0$ with radius GM/h.

Kepler's first law We choose our coordinate system so that $\boldsymbol{j}$ is in the direction $\boldsymbol{v}_0$, i.e.,

$$\boldsymbol{v}_0 = v_0\boldsymbol{j} \qquad \text{where } v_0 > 0. \tag{21}$$

Thus, equation (20) becomes

$$\boldsymbol{v} = \frac{GM}{h}[-\sin\theta\,\boldsymbol{i} + (\cos\theta + e)\boldsymbol{j}] \tag{22}$$

where $e = v_0 h/GM$. Substituting equation (22) into equation (4) and using equation (6), we get

$$h\boldsymbol{k} = \boldsymbol{r} \times \boldsymbol{v} = \frac{GMr}{h}[\sin^2\theta + (\cos^2\theta + e\cos\theta)] = \frac{GMr}{h}(1 + e\cos\theta)\boldsymbol{k}.$$

and hence

$$r = \frac{h^2}{GM}\frac{1}{1 + e\cos\theta} = \frac{k}{1 + e\cos\theta} \tag{23}$$

where $k = h^2/GM$. In order for r to remain finite for all θ, we must have $0 \le e < 1$. Equation (23) is the equation of an ellipse in polar coordinates with the origin at one focus. This completes the proof of Kepler's first law.

Kepler's third law Since the rate that area is swept out by the position vector is the constant $h/2$, it follows that

$$A = hT/2 \tag{24}$$

where T is the period of the motion and A is the area of the ellipse. Since translation doesn't change the area, we can consider the area of the ellipse

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1. \tag{25}$$

We will calculate the area of the first quadrant ($x \geq 0$, $y \geq 0$) and multiply by 4. Solving for y as a function of x from equation (25), we obtain

$$y = b\sqrt{1 - x^2/a^2}, \qquad 0 \leq x \leq a.$$

Thus, the area A is given by

$$A = 4b \int_0^a \sqrt{1 - x^2/a^2}\, dx. \tag{26}$$

If we make the change of variables $x = a \sin\phi$ ($dx = a \cos\phi\, d\phi$) in the integral, we obtain

$$A = 4ab \int_0^{\pi/2} cos^2\phi\, d\phi = 4ab \int_0^{\pi/2} \frac{1 + \cos 2\phi}{2}\, d\phi = \pi ab. \tag{27}$$

Substituting this value for A into equation (24),we obtain

$$T = \frac{2\pi ab}{h} \qquad \text{and hence} \qquad T^2 = \frac{4\pi^2 a^2 b^2}{h^2}. \tag{28}$$

Using equations (15) and(16) along with the relation $k = h^2/GM$, we can write the expression for T^2 in equation (28) as follows

$$T^2 = \frac{4\pi^2 k^4}{(1 - e^2)^3 h^2} = \frac{4\pi^2 k a^3}{h^2} = \frac{4\pi^2 a^3}{GM}. \tag{29}$$

Equation (29) is Kepler's third law.

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