Physics 419: Lecture 2: Spheres, Ferris Wheels, and Heresy
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Few problems in science have proven as difficult to resolve as that of the annual motion of the planets and the diurnal cycle of the sky. To understand why this problem was so intractable requires turning the clock back to ancient times when the first notions of the cosmos were just being formed. This is particularly difficult to do because while we can contribute to knowledge we cannot subtract from it. Hence, the best we can hope to do is suspend momentarily our current knowledge of the universe and think back to the time when we knew nothing. Imagine your first time as a child when you saw the sun. You noticed that the sun shone during the day and disappeared at night. At night the sky was not entirely dark however. New objects appeared, some bright, and some not so bright. You fixated first on the brightest object in the sky, the moon, which was also the closest. You also noticed that its position in the sky changed from day to day. Upon further observation, you noticed that most of the other bright objects in the sky remained basically fixed except for a few vagabond stars. Night after night you kept track of the vagabond stars. You gave them names: 1) Sun, 2) Moon, 3) Mercury, 4) Venus, 5) Mars, 6) Jupiter, 7) Saturn. As far as you could tell everything else remained stationary in the sky. After a few years of such observations, you noticed that these stars returned to their original locations. You repeated these observations many times and the results were always the same. It is this body of observational knowledge that befuddled the first star gazers. Simply stated the problem was to explain 1) what accounts for day and night that is, the diurnal rotation of the sky and 2) what model explains the motion of the planets. If it were not for the vagabond stars, the problem would have been quite simple. However, nature is what it is and it is the complexity introduced by the planetary cycles that made this problem the leading scientific problem from the Babylonian age (3000 B.C.E.) to the time of Copernicus and Galileo. This problem was not considered solved until well into the 17th century. It is the evolution of ideas introduced to solve this problem that we focus on in this lecture. As the answer to this problem undoubtedly involves choosing a reference point for the universe, the resolution of this problem brings out clearly human bias, the importance of psychology and ultimately man's attempt to impose a human theme on the universe. To this end, many far-fetched theories were proposed as is the case with any unsolved scientific problem that is of great importance. As you will see, Plato and Aristotle presented the largest roadblock to the final solution. Their ideas followed from a rational system that was not based on nature but rather the world of the forms. In fact, I will argue that Copernicus was not really ready for the Copernicun revolution and remained firmly wedded to the key tenets of Aristotelianisms until his death. While Plato and Aristotle were important philosophical figures, their ideas were wrong but because of their lasting impact in Western thought, the authority of their ideas served to guide the direction of astronomy in the completely wrong direction for nearly 2000 years. In fact, in 1536 at the Sorbonne, a few years before Copernicus published his reluctantly-revolutionary work, *de Revolutionibus*, Pierre Ramus received an ovation for his thesis entitled, "Whatever is in Aristotle is false." (see Koestler, p. 201) But this is getting ahead of the story. We will outline in this lecture the genesis of earth-centered and helio-centered views of the cosmos starting from the first written accounts of attempts to solve this problem.

While none knew just how to solve this problem, their was no shortage of experimental data on the cosmos. Clay tablets from the region of Sargon of Akkad in 3800 B.C.E. show that 1) the length of a calendar year was known to within .001% of its current value, 2) the error bars on the motions of the sun and the moon were only a factor of three larger than the results of extensive measurements in the 19th century when powerful telescopes became available, and 3) the motion of the planets was confined to a narrow lane (termed the zodiac) in the sky about 23^o to the equator. The zodiac was divided into twelve sections, each section named after a constellation of stars in the vicinity. These basic facts of the cosmos were not in dispute. What was missing was a coherent picture of how day became night and how the planets moved.

1 Pre-Pythagoreans

In the absence of a telescope, the most obvious theory that can account for the diurnal cycle is a static earth and a moving sun. Initially this seems plausible because observers on the earth do not detect any perceptible motion of the earth. What seems to move is the sun. While this certainly contributed to the genesis of geo-centered universes, the primary reason lies elsewhere. Both religion and human psychology dictated that man is the center of the universe. Deeply felt was the view that the earth is not simply one of the many planets whirling about the cosmos. It is predominantly for this reason that all early proposals for the diurnal cycle of the sky placed the earth at the center and the sun and the planets revolving around it. The first written account of how this happens is due to the Ionian philosophers. Thales of Miletos, as did Homer, proposed that the earth is a circular disk floating on water. Other Ionians such as Anaximenes, an associate of Anaximander, proposed that the stars and planets are nailed into some sort of crystalline transparent sphere that turned around the earth. The sphere turned much the way a hat does on your head. On this account everything in the sky would turn at the same rate and have the same brightness. This account clearly does not work. But nonetheless it serves to illustrate how a conceptual bias affects the construction of a theory of the physical world.

2 Pythagoreans

Enter Philolaus of the Phythagorean school. Central to Pythagoreanism were 1) the universe was created and exists based on a divine plan, 2) numbers are sacred (eternal even while everything else is perishable), 3) there is harmony in music which is based in numbers, and 4) 10 is the most sacred of the numbers. His key innovation was to realize that a moving earth could account for the diurnal cycle. While rotation of the earth about its axis would be the simplest solution, Philolaus proposed instead that the earth rotated every 24 hours around a fixed point in space. An observer on the earth has the illusion of everything else rotating in the counterclockwise direction. But this is where Philolaus loses it. He then proposes that the center of the universe is the 'watch tower of Zeus' also called the 'hearth of the universe' or equivalently the central fire. To protect parts of the earth from being scorched, Philolaus placed an invisible planet, called the *antichton*. Then comes the outer sphere of the Ionians. In this account, eclipses are caused by the earth or the counter earth or both. There are 10 objects (Earth, moon, 5 planets, antichton, central fire, sun) in all in this universe, not an accident given that they thought the 10 was the most special number. The moon was thought to be inhabited by plants and animals. The time was 600 B. C. E.

3 The Birth of Helio-centrism: Heraklides

By 400 B.C.E., Herakleides took Philolaus' proposal two steps further. The first step was to let the earth rotate on its axis. Simple geometry told him that an internal reference point as opposed to some arbitrary external point would accomplish the daily cycle of night and day. So at the center of the universe is a spinning earth with a 24 hour rotation cycle. What about the planets? By Herakleides' time, new data was available on the precise motion of the planets. All six planets moved in irregular ways. Venus was particularly troublesome.

Venus seemed to change in brightness and size indicating accession and recession from earth. Further, it seemed to have an orbit that was tied more to that of the sun than to the earth. In fact, Venus at times appeared to rise with the sun and also appeared in the evening at the tail of the sun. The 'morning star' was known as Phosphoros and the 'evening star' as Hesperos. There was quite a period of time when Phosphoros and Hesperos were thought to be two distinct planets. Herakleides reasoned that if Venus has an orbit that is irregular relative to the earth then maybe its center of revolution is not the earth afterall. He also applied the same reasoning to Mercury, the second inner-most planet for which similar irregularities were observed. He then proposed that in fact, the sun is the center of the orbit of both Venus and Mercury. So Herakleides' system is as follows: 1) spinning earth at the center, 2) Venus and Mercury orbiting the sun and all three are orbiting the earth, and 3) all the other planets orbit the earth at varying radii depending on their distance from the earth. Interestingly, Tycho Brahe resurrected this view after Copernicus proposed the sun-centered universe. You should try to determine at which point this scenario can be ruled out with certainty.

3.1 Aristarchus

The last of the Phythagorean astronomers was Aristarchus. Born in 310 B.C.E., the year of the death of Herakleides, Aristarchus saw no reason to retain the earth as the focal point for the other three remaining distant planets. He proposed instead that the sun is the center of the universe and all the planets orbit the sun at fixed radii. However, for the next 1500 years his work was ignored as Plato and Aristotle proposed preposterous idea upon improbable idea to account for planetary motion. Their views culminated in what would be called today, the Ferris wheel model of the universe.

4 Plato and Aristotle: Unmoved movers and spheres

For aesthetic and philosophical and religous reasons, Plato rejected a helio-centered world. Plato argued that the stars, regardless of their beauty, are part of the visible world which is but a bad imitation of the real world of ideas. Hence, any attempt to determine the exact motion of the planets is a waste of time. He also argued that the ' the shape of the world must be a perfect sphere, and that all motion must be in perfect circles at uniform speed.' As is evident, Plato was not too concerned with the way things actually are. Plato takes a top-down approach. He determines the structure of the physical theory *a priori* and then he and his disciples went about to mold and mangle the world to fit this view. You should beware that this is a classic example of how not to do science. The only thing left for Plato to do was hire disciples who could work out the mathematical details to make his scheme work. To his aid came Eudoxus and Calippus. The problem they had to solve was how within an earth-centered universe can one account for the slowing down and apparent reversal of the pathway of the planets. To solve this problem, they assigned to each planet several spheres. The goal was to allow for more degrees of freedom to account for the bizarre motion of the planets. So this is what they did. Each planet was attached to a point on the equator of a sphere. The sphere rotates on its axis. This sphere is now placed in a concentric larger sphere. The inner sphere is attached to the larger sphere at the axes. This larger sphere now rotates about a new axis. And so on and so on. The planet will then engage in all the independent rotations associated with the various axes of the spheres and hence large irregularities in the speed and path of rotation can be generated. In Callipus' scheme 34 spheres were needed.

Aristotle saw that the Callipus scheme was lacking 20 spheres if it were to be a physically realizable system. The extra spheres were neutralizing spheres which turned in the opposite direction of the working spheres. These functioned basically as ball-bearings so that the motion of one planet would not be communicated to that of the others. So from Aristotle and Plato, we have spheres in spheres connected by ball-bearings to account for the planetary motion. Getting the whole system moving required 55 unmoved movers. If the problem of the origin of the 55 unmoved movers was not daunting enough, an additional problem with this approach is that the distance of all the planets from earth remains fixed in this spherical picture. It was known at the time, however, that the earth-planet distances changed throughout the yearly cycle of the earth. Hence, this theory was doomed from the beginning.

Aristotle was also instrumental in providing a rationale for why the earth could not be moving. He divided physical effects into natural and violent ones. A moving earth would have no way of retaining its atmosphere. Everything would fly away from it as a result of the centripetal force. Such violent motions cannot be part of nature, according to Aristotle.

4.1 Ptlomey: Ferris Wheel universe

Enter the Ferris Wheel model of Ptolemy of Alexandria, 200 A. C. E. Here he basically perfected the work of Hipparchus and Apollonius of Perga in 300 B.C.E. Rather than describing this in words, I will refer you to the picture that accompanies this lecture. Here Ptolemy has a new invention: epicycles and deferrents. The deferrent is the giant Ferris Wheel and the epicycles are the cycles the cars make on the Ferris Wheel. By choosing suitable ratios for the diameters of the deferrents and the epicycles, one could reproduce quite accurately the motion of the planets. By this time, however, it was clear that some of the planets had actually elliptical orbits. But because everyone was constrained to use circles, an even more inventive step was made. The hub of the wheel no longer coincided with the earth but was movable to reproduce the desired elliptical orbit. This sort of craziness was mandated by the Platonic dictum that only circles be used. Nonetheless, the work of Ptlomey was a big success in that it was widely accepted as being true. In fact, Galileo held this view to be self-evident throughout his life.

4.2 Theoretical considerations

Should you be worried at this point with the obvious question, how could such great minds have been so misguided? Not really. All of you know the answer. The telescope and a general theory of gravity were not available at the time. In fact, there was no real rationale for assuming that the earth moved. There was no parallax observation of any kind. Now an amateur astronomer could easily verify that Venus and Mars go around the sun and Jupiter has four moons. From these observations, one could easily infer that in all of these cases, the lighter object is always circling the heavier object. So why does not the earth go around the sun. Once one has a theory of gravity, then the answer to this question is of course, the earth goes around the sun. But in the absence of such an adequate theoretical account, wild conjectures are often made. These can be ruled out by either further experimentation or a theoretical model that is so simple and physically plausible that it must be accepted. None had been proposed thus far.

5 Copernicus: Helio-centrism revisited

This was pretty much the state of things until the time of Copernicus. What is interesting to note however is that Copernicus did not have any more data than did the ancients. In fact, he was not an observer himself. He relied entirely on the data of the Chaldean priests, the Greeks and the Arabs. His original name was Canon Nicolas Koppernigk. He was born in 1473 in what was Royal Prussia. He attended university at Cracow and spent some time in Rome. He returned to Prussia, however to do most of his work. He was known to be acutely secretive, cautious and oblique, traits that contributed undoubtedly to his reluctance to publish *de Revolutionibus.* In 1509 A.C.E., he published the precursor of his helio-centered universe entitled *Commentariolus.*

Copernicus' motivation from the start was to make the Ptolemaic system more consistent with an Aristotelian universe. In Ptolemy, each planet moved in epicycles and hence did not have a uniform speed in its entire orbit. Copernicus objected: 'Having become aware of these defects, I often considered whether there could perhaps be found a more reasonable arrangement of circles... in which everything would move uniformly about its proper centre as the rule of absolute motion requires.' So you see, Copernicus held as a self-evident truth the Aristotelian dictum that uniform motion in perfect circles is inviolate. The key tenets of his view were as follows: 1) the heavenly bodies do not all move round the same center; 2) the earth is not the center of the universe, only of the moon's orbit and of terrestrial gravity; 3) the sun is the center of the planetary system and therefore the universe; 4) compared to the distance of the fixed stars, the earth's distance from the sun is negligibly small; 5) the apparent daily revolution of the firmament is due to the earth's rotation on its own axis; 6) the apparent annual motion of the sun is due to the fact that the earth, like the other planets, revolves around the sun; 7) the apparent 'stations and retrogressions of the planets are due to the same cause.' He then in seven chapters outlines how many circles and epicycles are needed to reproduce the precise orbits of the planets. Hence, while Copernicus had broken from the past in that the sun was now at the center of the universe, he still held onto the basic tenents of the Ferris Wheel universe. This is undoubtedly the pernicious influence of Plato and Aristotle and their *a priori* insistence on circular orbits. Nonetheless, the news of Copernicus' helio-centered world spread quickly and he was encouraged to publish his long-awaited *de Revolutionibus.* Here is a letter from Cardinal Nicolaus Schoenberg, who occupied a positon of special trust under three succeeding Popes, Leo x, Clement VII and Paul III: '...I beg you most emphatically to communicate your discovery to the learned world, and to send me as soon as possible your theories about the Universe, together with the tables and whatever else you have pertaining to the subject...' (Koestler p. 155).

For any number of reasons, Copernicus remained reluctant to publish his longer work detailing his full theory. Here, in the dedication to his book to Pope Paul III, is some insight into why: '...I may well presume, most Holy Father, that certain people, on learning that in this my book *On the Revolutions of the Heavenly Spheres* I ascribe certain movements to the Earth, will cry out that, holding such views, I should at once be hissed off the stage,...Therefore I have doubted for a long time whether I should publish these reflections writen to prove the earth's motion, or whether it would be better to follow the example of the Pythagoreans and others, who were wont to impart their philosophic mysteries only to intimates and friends, and then not in writing but by word of mouth,...' (Koestler p. 152). The next installment came from a Copernicun disciple, Rheticus (born Georg Joachim von Lauchen in Austria) entitled *Narratio Prima*. Here he outlines the basic Copernicun theory. It appeared in print in 1539. Then finally came the long-awaited 212 page manuscript of *de Revolutionibus* which was published when Copernicus was on his deathbed. He died the year it was finally published, 1543. In it Rheticus is mentioned not even once. This betrayal of Rheticus did not go unnoticed by the astronomy community. Maybe it was for this reason that Copernicus made *de Revolutionibus* particularly opaque so that it was only accessible to expert mathematically minded astronomers. The first printing in 1543 of 1000 copies never sold out. In fact, it is likely that not even experts such as Galileo read this work. In this work, Copernicus makes it clear that although he has transferred the center from the earth to the sun, he still requires epicycles as he maintains the circular orbit approach of the Aristotelean school. In this sense, Copernicus was the last Aristotelean.

But how could Copernicus square motion of the Earth with the Aristotelian dictum that such motion is violent. The following quotations reveal how he countered:

‘Now it seems to me gravity is but a natural inclination, bestowed on the parts of bodies by the Creator so as to combine the parts in the form of a sphere and thus contribute to their unity and wholeness. And we may believe this property present even in the Sun, Moon, and Planets, so that thereby they retain their special form notwithstanding their various paths. ’ (Koestler p. 199)

‘But if one holds that the earth moves, he will also say that this motion is natural, not violent. Things which happen according to nature produce the opposite effects to those due to force. Things subjected to violence or force will disintegrate and cannot subsist for long. But whatever happens by nature is done appropriately and preserves things in their best conditions. Idle, therefore, is Ptolemy’s fear that the earth and everything on it would be disintegrated by rotation which is not an act of nature, entirely different from an artificial act or anything contrived by human ingenuity,’ (Koestler, p. 199)

That is, there is no centrifugal force associated with a rotating earth. Copernicus then turns the Aristotelian argument on its head. He poses that it is more absurd to assume that the universe is circling the earth because for it to do so, it would have to be moving faster than the earth around the sun and hence such a system is even more unstable. But on his own reading this argument is untenable. He knew this and countered with a purely Aristotelian argument appealing to the ‘earthiness’ of an object that would otherwise fall to the earth.

‘bodies which fall because of their weight, must, because of their maximum of earthiness, doubtless participate in the nature of the whole to which they belong.’ (Koestler, p. 200)

So it is clear that Copernicus is purely Aristotelian on three counts: 1) uniform motion in perfect circles is inviolate and 2) natural motion of the earth comes about from its spherical shape, and 3) earthiness keeps objects tethered to a revolving earth. Note earthiness is not a physical property but a metaphysical one that keeps objects tethered to the physical realm.

As Kepler said, 'Copernicus was guilty of interpreting Ptolemy not nature.' Copernicus was not ready for the Copernicun revolution.

However, the helio-centered universe did have a key advantage. If all the planets are moving around the sun at different radii, the movement of two planets relative to one another will be reversed once an inner planet overtakes an outer planet. Hence statis and regression fall out naturally from a helio-centered universe. However, Copernicus really did not put the center of the universe at the sun; he simply put the center in the vicinity of the sun. So in some sense, Copernicus has a vacuo-centric system. If you read Copernicus carefully, it becomes clear that the center of Saturn's orbit was outside the sphere of Venus' and the center of Jupiter's orbit was near the sphere of Mercury. Ultimately, this would lead to interference between the orbits. Hence, even the Copernicun system was untenable. Also, he needed 34 circles to explain the orbits of the planets. But he did provide the kernel of the idea which has persisted since his death–namely, heliocentricism.