Galileo and Kepler: breaking away from the ancients

Reference webpages:

http://en.wikipedia.org/wiki/Galileo_Galilei
http://en.wikipedia.org/wiki/Johannes_Kepler
http://en.wikipedia.org/wiki/Tycho_Brahe

In this lecture we will discuss two key figures in the movement towards modern science: Galileo Galilei and Johannes Kepler. Questions to bear in mind are:

1. What were the driving motivations of Galileo and Kepler? In particular, how modern were their approaches to science?
2. Why was Kepler's model of the solar system not widely accepted until decades after his death?
3. How did the emphasis on experiment transform science?
4. For a person in the early to mid 1600s, would the balance of evidence have favored the Aristotelian or the Galilean view of motion and gravity?

In the last 40-45 minutes of class we will have our second official debate, and it will be on the last of these four topics.

Kepler, Brahe, and the motion of the planets

To my mind, the story of Johannes Kepler is remarkable because in him we have a mystical figure who was driven by aesthetic considerations but who nonetheless placed agreement with observations above all such considerations. This uncompromising position led, after many tortuous months, to one of the most remarkable breakings of a mental block in the history of science.

Kepler was born in 1571 in Germany, into a family whose fortunes had fallen. His father left when he was five years old, and his mother was weird enough that late in her life she was tried for witchcraft (a charge against which Johannes successfully defended her). His early interest in astronomy was stimulated by his observation of the Great Comet of 1577 (which the older Tycho Brahe showed had to be farther than the Moon was, thus casting doubt on the stability of the heavens) and of a lunar eclipse in 1580, but his weak vision and crippled hands meant that he personally could not conduct adequate observations of subtler phenomena. He demonstrated early aptitude in mathematics, and in 1594 became a teacher of mathematics and astronomy at a school in Graz, Austria. One of his duties was to make astrological forecasts, and he was quite successful at this: he predicted a cold winter and an invasion of the Turks, both of which happened. However, he never fully bought into astrology, referring to it as the foolish daughter of a wise mother (astronomy), and chafing at its imprecision compared to astronomical calculations.

As a theology student at the University of Tübingen, Kepler had become a committed Copernican. He therefore accepted that the orbits of the planets were circles centered on the Sun (modulo epicycles and whatnot), but the radii of the orbits seemed arbitrary. Then, on July 19, 1595, while teaching in Graz, he had a dazzling epiphany: if one inscribed a circle in a regular polygon, then circumscribed a circle around the same polygon, one had a unique ratio of the radius of the inner circle to the outer. Perhaps this would provide the reason for the particular ratios of the solar system. The problem was that there are an infinite number of regular polygons, but that even so there was no arrangement he could find that would give ratios consistent with observations. Later, he had an even better idea. There are five regular polyhedra, and six planets were known then (Mercury, Venus, Earth, Mars, Jupiter, and Saturn), and he discovered that starting with an inner sphere and doing the inscribe/circumscribe bit with, successively, an octahedron, icosahedron, dodecahedron, tetrahedron, and cube would yield the radii within the accuracy limits at the time. To the end of his life, Kepler considered this to be his greatest contribution to astronomy.

That's an odd thought from the modern perspective, because it is completely wrong. For one thing, two more major planets are known (Uranus and Neptune). For another, many other planetary systems are known that don't come close to following this arrangement. In addition, with our much more precise measurements the system doesn't even work for the inner six planets. To Kepler, however, the system seemed so right, so perfect, that it had to be true. To me, this is a lesson about how easy it is for our aesthetic predilections to get the best of us. However, Kepler's later work suggests to me that if he had been confronted with what we know now, then he would have given up his cherished idea. His ability to abandon concepts that do not fit the data was truly remarkable.

In the next few years, Kepler published his work and corresponded with various astronomers. Much of his additional work during this period strikes us now as completely mystical; for example, he assumed that the Earth had a soul, and that this is how the Sun causes its motion(!). However, towards the end of the 1500s he became increasingly frustrated by the inaccuracy of astronomical data, and he also became nervous due to growing religious tensions in Graz. Fortunately, Tycho Brahe invited Kepler to visit him in Prague, and Kepler set off on January 1, 1600. Tycho was the greatest observational astronomer of his day, so we will divert to give a portrait of him as well as to set the stage for Kepler.

Tycho Brahe

Tycho was a Danish nobleman born in 1546 who initially studied law at the University of Copenhagen. The solar eclipse of August 21, 1560 impressed him, particularly that it had been predicted, and his interests began to divert towards astronomy. He must have been an interesting fellow: at the age of 20 he lost the bridge of his nose in a duel with another nobleman, and he probably died of uremic septicemia brought on because he refused to leave a Prague banquet to relieve himself (it would have been a breach of etiquette). To add to the mystery, there have been recent suggestions that he instead was poisoned with mercury, which would have been an interesting fate for someone who studied the planets!

Tycho's fame in astronomy stemmed largely from his observations of the supernova of 1572. Ancient astronomers had taken as given that whereas the Earth is changeable and corrupt, the heavens are pristine and constant. Thus comets were considered to be atmospheric phenomena, or at least inside the orbit of the Moon (which is close enough to be considered susceptible to Earth's corruption). However, on November 11, 1572 Tycho and others noticed a new and bright star in the direction of the constellation Cassiopeia. At its peak this star was as bright as Venus, and it was visible in the daytime for about two weeks.

Such objects had been seen a few times before, but only once every few centuries on average. The difference in this case was that Tycho noted that the apparent position of this object relative to the fixed stars did not change over the night. The reason this is important is that for a close object one would have expected to see *parallax*, which is most easily demonstrated by holding a finger out and noting that it appears to change position relative to a background wall when you look at it with just your left eye, then just your right. The farther your finger is from you, the less it appears to move. Given the precision of Tycho's observations, this new object had to be farther than the Moon. Even more surprising was that over the months that the new object was detectable with the naked eye (which was all that was available prior to the invention of the telescope in 1609), it did not appear to move at all relative to the fixed stars. Even for those who believed that the Earth was stationary, this put the new object in a different category than the planets, which all moved palpably over months. This set of observations thus demonstrated unequivocally that the heavens do in fact change.

The fame produced by Tycho's book "De nova stellar" about these observations led King Frederick II of Denmark to offer Tycho the use of the island of Hven for his observations. Tycho built an observatory he called Uraniborg in 1576, and with his large coterie of assistants made highly precise naked-eye observations (augmented by specialized tools) until 1597, when disagreements with Frederick's successor Christian IV escalated to the point that Tycho departed. He found new sponsorship in Prague from Rudolf II, the Holy Roman Emperor of the time, and invited Kepler there in 1600.

Initially Tycho was highly guarded with his data, but Kepler impressed him enough with his theoretical ideas that Tycho granted Kepler more access to the data. After a series of ups and downs, Kepler worked with Tycho throughout most of 1601, and on Tycho's death on October 24, 1601 was appointed his successor as Imperial Mathematician.

Kepler with Tycho's data

Kepler's main duties, in addition to the casting of horoscopes, involved the completion of the Rudolphine Tables, which would replace existing astronomical tables. On his deathbed, where Tycho named Kepler his successor, he expressed his hope that Kepler would present the tables using Tycho's proposed model of the solar system. This model, which now strikes us as an ugly hybrid, has it that the Sun and Moon orbit the Earth, but the other planets orbit the Sun. It can be thought of as a last attempt to place the Earth in a favored position (as the only unmoved object) while allowing the Sun to be the center of some motions.

Kepler then went to work, but found small but persistent discrepancies that bothered him. Tycho had suggested that Kepler analyze Mars in particular, and Kepler found that no matter how he adjusted his equants and other complications, the data didn't quite fit. The deviation was small; the maximum discrepancy was eight minutes of arc, which is the angular size of a penny at a distance of eight meters. Most people in history would have dismissed this as of no consequence, but Kepler was agitated by the difference because he knew that Tycho's observations were much better than this (the median error was about 1.5 arcminutes, the angular size of a penny at more than forty meters). He therefore obsessed about this for years.

His first breakthrough was to consider that perhaps the speed of the orbit varies with the distance from the Sun (recall that Kepler was a Copernican, and thus did not believe Tycho's model). This has similarities to the known properties of magnetism and the intensity of light, so these served as motivation. He found, empirically, that planets sweep out equal areas in equal times, and formulated this law (now known as Kepler's second law) in 1602.

The next question was the shape of the orbit. He thought about egg-shaped orbits, and made more than 40 attempts to fit Tycho's data until finally in 1605 (and after multiple arithmetic errors) he came to the possibility of an ellipse. An ellipse is one of the classic conic sections (i.e., it is a shape that can be produced by the intersection of a plane with a cone), and Kepler had assumed that this was too simple to have been overlooked by other astronomers. Instead, no one previously had had the insight needed to consider ellipses, and (equally importantly) no previous astronomer had access to such precise data. With this, Kepler produced what is now called his first law: all planets move in ellipses, with the sun at one focus. In 1619 he added his third law: the period of an orbit is proportional to the three-halves power of the semimajor axis. He finally completed the Rudolphine tables in 1623, publishing them in 1627, and died in 1630. In his last twenty years he also wrote what is now considered to be the first science fiction novel, successfully defended his mother against witchcraft charges, and performed sundry other investigations into optics and mathematics.

As a side comment, from the perspective of history I find it a little strange that no one came up with the idea of elliptical orbits prior to Kepler. Comets moved in obviously noncircular orbits, and indeed this led Tycho to conclude that there could not be literal celestial spheres, as the comets would puncture them. However, no one thought that the planets might move similarly.

To restate Kepler's laws in a concise form:

1. Planets move in ellipses, with the Sun at one focus.
2. The line from the planet to the Sun sweeps out equal areas in equal times.
3. The square of the period of the orbit is proportional to the cube of the semimajor axis.

Reception of Kepler's astronomy

The agreement of Kepler's three laws with the most precise data of the time, including subsequent telescopic data, was so spectacular that one might suppose that astronomers were immediate converts. This was, however, far from the case. A contributing factor was undoubtedly that Kepler was renowned for the impenetrability of his prose (and of his oral delivery as well; he was apparently a horrendous lecturer). This may have been a reason that Galileo, his senior by just seven years, disappointed Kepler by never responding to his astronomical works even though the two corresponded on other matters and even though Galileo recommended Kepler for a position as mathematician at Padua when Galileo departed in 1611. In addition, there were some missed predictions: for example, the transit of Venus across the Sun in 1631 was predicted incorrectly because of some mistakes in the Rudolphine table. Finally, in addition to the bare-facts astronomical model presented by Kepler he added many physical and metaphysical elements, some of which really were weird (such as the magnetic soul of the Earth). It took several decades, indeed until the ascendancy of Isaac Newton, before people were sufficiently confident of being able to sort out the useful from the useless that Kepler's planetary model was accepted fully.

With this in mind, we now turn our attention to Galileo and the search for physical models to replace the ideas of Aristotle.

Galileo and astronomy

Galileo was born in Pisa in 1564, and is often considered the first fully modern physical scientist, in that he emphasized quantitative measurements and mathematical models (about which we will discuss much more in the next lecture). His early curiosity is indicated by the story that when he was 17 he went to Mass in Pisa and noticed that the oscillation period of a swinging chandelier was approximately independent of how far it swung (the time actually increases, but only slightly, for larger swings in a vacuum). In 1589 he became a mathematics professor, then moved to Padua in 1592, where he taught geometry, mechanics, and astronomy. Although he made various important discoveries in the kinematics of motion and the strength of materials, he seemed fated to be a footnote in the history of science.

This changed in 1610. Galileo had heard of the invention of the telescope by Hans Lippershey in 1608, and soon improved the design (and presented it without necessarily acknowledging Lippershey!). He became wealthy with his design, because such devices were highly useful to sailors. He also quickly made a number of observations of the heavens. These observations, which were published in the popular book "Sidereus Nuncius" (Starry Messenger), revolutionized astronomy and made Galileo an international scientific superstar.

In this book and work over the next two years, Galileo:

- Showed that Jupiter has its own moons, which orbit Jupiter and move with it. Previous generations had argued that if the Earth moved it would leave the Moon behind, but this provided a clear counterexample.
- Showed that Venus exhibits a full set of phases. This was strongly contrary to the predictions of geocentric models, in which a full Venus was never expected.
- Popularized the existence of sunspots. These had been seen centuries earlier by non-European astronomers, and had even been observed by Kepler (who thought it was a transit of Mercury). Galileo's observations showed that these were not clouds but actual features of the Sun, and that the Sun rotates; this confirmed a dramatic prediction made by Kepler in 1609.
- Showed that the Milky Way actually consists of countless numbers of stars instead of being nebulous.
- He actually discovered Neptune, but did not realize that it was a planet because he did not follow it long enough to see its motion relative to the fixed stars.

Interestingly, Galileo dismissed Kepler's ellipses because he considered circular orbits to be perfect (shades of Aristotelian aesthetics!), and also dismissed Kepler's correct idea that the Moon was at least partially the cause of tides. In general, Galileo frequently engaged in heated polemics against those with contrary ideas, which probably contributed significantly to his later difficulties with the Catholic church.

Galileo and the physics of motion

Important though Galileo's contributions to astronomy were, one could make a case that his role as the first experimental physicist were even more seminal. It is true that many of his ideas had been proposed before. For example, the idea that all weights would fall in the same manner in a vacuum had been proposed by Lucretius. More specifically, the idea that if resistance is neglected a body falls with constant acceleration had been proposed Domingo de Soto in the 1500s. Even the idea that velocity is constant unless the object is acted on by a force had been proposed previously.

What, then, were Galileo's specific contributions? In a way that is qualitatively distinct from his predecessors, Galileo emphasized quantitative measurements and mathematical modeling. For example, in order to measure the motion of falling objects he rolled or slid objects down inclined planes in order to slow down the motion and make it measurable using very primitive timekeepers (such as his own pulse). He then used mathematics, mainly geometry, to express the laws precisely. He also used thought experiments centuries before Einstein to make various concepts clearer.

An example of such a thought experiment relates to the motion of falling objects. Suppose that Aristotle's ideas are correct, and thus that heavy objects fall faster than light objects. Now imagine two blocks, one on top of the other, that are connected vertically by a short and slender thread. If we drop them together then we expect them to fall as a single heavy object, that is, rapidly. If we repeat the experiment but cut the thread just before dropping, Aristotle would have us believe that the blocks would know to fall more slowly, no matter how short and slender the thread was initially. This is absurd, therefore, we can discount Aristotle's idea.

Another of Galileo's thought experiments presages Einstein's ideas of relativity, and establishes what is therefore called Galilean relativity. An argument against the rotation or orbit of the Earth was that objects not nailed down (such as clouds or birds) would be left behind by this motion. Galileo asked us to imagine the hold of a ship that is moving smoothly and uniformly across the water. Such a situation would have been familiar to his readers. A person riding in the hold could perform various experiments. For example, they could throw an object straight up, or observe water dripping straight down. Aristotelian physics would have us believe that the object and the water would be left behind, i.e., would seem to drift sideways. However, experience tells us that this is not so; indeed, all such experiments yield the same results as if we were stationary on solid ground. More generally, Galileo and later Einstein said, it is only *relative* motion that can be discerned. This is a fundamental principle of physics.

Galileo and the Church

The story of Galileo's battles with the Catholic Church are often oversimplified. Several passages in the Bible can be interpreted as saying that the Earth does not move. Galileo argued, following Augustine, that these passages need not be taken literally. However, attacks on Copernicanism intensified to the extent that in 1616 Galileo went to Rome to try to prevent his ideas being banned. He was ordered not to defend the idea that the Earth moves and the Sun stands still, but this allowed the loophole of Galileo discussing the heliocentrism “hypothesis”. In 1632 he wrote “Dialogue Concerning the Two Chief World Systems”, in which he made his character Simplicio the defender of the geocentric position; the name has the connotation of “simpleton”, so the fact that Simplicio ineffectively parroted the views of Pope Urban VII (Galileo’s erstwhile supporter Cardinal Barberini) meant that the Galileo had offended one of his most powerful supporters. He stood trial for suspicion of heresy in 1633, and was required to abjure his opinions. He was also put under house arrest for the rest of his life and his works were banned. During his house arrest, where he eventually went blind, he wrote “Two New Sciences”, which contained profound discussions of kinematics and material strength.

This entire affair is often presented as a battle between religion and science, and those elements do exist. Indeed, I cannot seen any justification, ever, for imprisoning someone based on their scientific beliefs because it conflicts with religious belief. However, there were many other currents at the same time. These include the Thirty Years’ War, the ongoing battle of the Catholic Church against incursions by Protestantism, and Galileo’s own lack of diplomacy (to put it mildly!). It seems likely that had Galileo simply presented his physical arguments and observations, rather than irritating supporters multiple times and seeming to take every opportunity to humiliate opponents, he would have been able to pursue his heliocentric views with little trouble. That being said, however, when we note that the uncensored versions of the Dialogue and De Revolutionibus (the heliocentric work of Copernicus) were only taken off the Church’s Index of Forbidden Books in 1835, it is hard to look at the Church as the aggrieved party!

Along these lines, it is useful to quote the words of then-Pope John Paul II in 1992, when he specifically vindicated Galileo: “The error of the theologians of the time, when they maintained the centrality of the Earth, was to think that our understanding of the physical world’s structure was, in some way, imposed by the literal sense of Sacred Scripture...”. It is useful to keep this in mind when considering the more modern opposition to biological evolution (not by the Catholic Church, which has indicated its acceptance of the overwhelming evidence, but by fundamentalist Protestants and fundamentalist Muslims among others).

In summary, Galileo and Kepler were two of the towering figures in the history of science, and their work, bolstered by extensive comparison with observations, revised our understanding of motion and gravity. To fully bring us into the modern concept of science, however, required another individual who was born on Christmas day in 1642, the same year Galileo died. His name was Isaac Newton, and his life and ideas will be the focus of our next lecture.