A Look at the Astrolabe

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The History

The origins of the astrolabe date back to ancient Greece, although some of its mathematical principles were probably influenced by Babylonian techniques. The evolution of the astrolabe continued for two millennia and would require its own treatise to explain its many uses. One of the earliest known makers and user of the astrolabe is thought to be Hipparchus. It is not known if he actually had an astrolabe, but his work in mathematics and astronomy indicates that he had an instrument of the astrolabe type (North, 1995).

Hipparchus was a Greek who was born in Nicaea (modern day Iznik, Turkey) in northwest Asia Minor. He worked mainly on the Greek island of Rhodes and thrived between 150 and 125 BC. Much of his problem solving technique seems to have been arithmetical and it is thought that he enlarged on Babylonian techniques as much of his work was influenced by the Babylonians. He is given credit as being the first Greek astronomer known to have thoroughly applied arithmetical methods to geometrical astronomical models. His work began the shift in Greek astronomy "away from qualitative geometrical description and toward a fully empirical science" (North, 1995, p. 102). He was also an important contributor to the foundation of trigonometry. In order to link geometrical models to observational data, something similar to trigonometry had to be used (North, 1995).

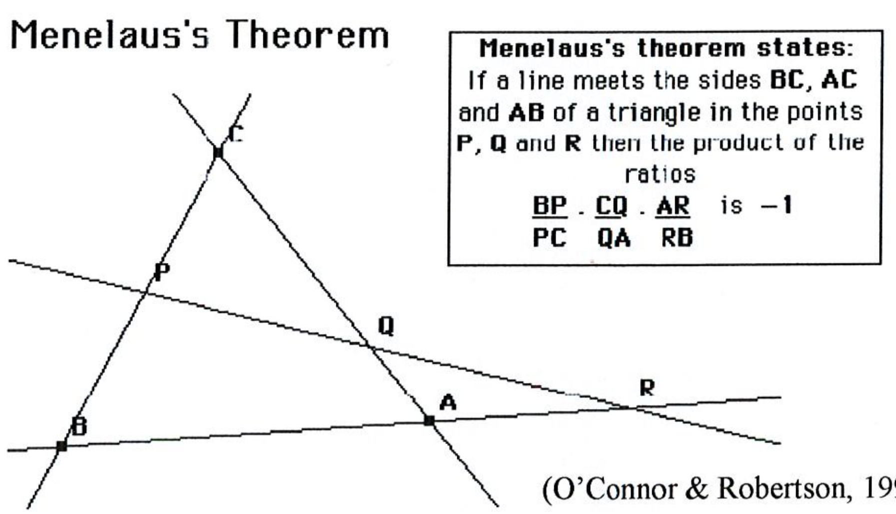
Hipparchus' work marks the beginning of a system of rigorously applied star coordinates. During his time, there was not the "pure" system of ecliptic latitude and longitude or of declination and right ascension that exists today. The systems that do exist today have gradually evolved from his work. Hipparchus did build his own star catalogue. He did not have coordinates for each star, in some cases he just gave comments about stars that were in line and estimates of distance. During his observations of stars, he noticed a new star and realized that it was moving. This caused him to wonder if other stars moved as well. He found that all stars have small motions parallel to the ecliptic and that ecliptic longitudes increase (North, 1995). These discoveries were important in the development and construction of the astrolabe.

The work of Greek mathematician Eudoxus shows that three-dimensional geometry was highly developed among the Greeks, so it is probable that Hipparchus broke down problems on the surface of a sphere into problems involving circles and triangles in a plane. An example of this would be problems concerning the risings and settings of the sun and stars, which is also a component in the development and construction of the astrolabe. Another geometrical method is one that involves a three-dimensional celestial sphere to be projected on a plane, much the way the Earth's surface is projected onto terrestrial maps. There is very little doubt that Hipparchus did in fact use this technique successfully (North, 1995).

Hipparchus' sole surviving work, known as *Commentary on the Phenomena of Aratus and Eudoxus*, is an example of a typical scholarly work during this time period. Eudoxus of Cnidus (about 390-340 BC) described a calendar with references to the risings and settings of the constellations known as the "Phenomena." Aratus (about 315 – before 240 BC) utilized Eudoxus' work and produced a highly popular poem also titled *Phenomena*. Mathematician Attalus of Rhodes wrote a commentary on both works and then Hipparchus followed suit. These works were not a new tradition among scholars. There is a surviving Babylonian text from around 700 BC that lists twenty sets of stars that culminate at the same time, showing that matters of the stars have long been a human concern. The difference between Hipparchus' work and the work of those who came before him was that he listed the degrees of the ecliptic that rose and set at the same time as the stars. The number of degrees is called the "mediation" of the star.

The purpose for this was to allow astronomers to tell the time at night when they were making their observations. The use of an instrument of the astrolabe type probably helped Hipparchus perform the necessary calculations. It is known that he had a three-dimensional globe with the constellations indicated on it (North, 1995).

Little is known about the development of Greek astronomy between the time of Hipparchus and that of Ptolemy. One mathematician who should be mentioned is Menelaus of Alexandria. He was active a generation before Ptolemy and he provided a worthwhile theorem for calculation in spherical astronomy in his book, *Sphaerica* (North, 1995). In this book he dealt with spherical triangles and their application to astronomy. He was the first to write down the definition of a spherical triangle. He treated spherical triangles as Euclid treated plane triangles.



(O'Connor & Robertson, 1999)

Another person worth mentioning is the great Greek architect Vitruvius (who died sometime after AD 27). He had described a water clock capable of showing the seasonal hours of day or night, and from his description, it had a sort of astrolabe as its dial. The apparatus as a whole is called an "anaphoric clock" (North, 1995).

Ptolemy was born around AD 100 and died about seventy years later. He was an astrologer, astronomer, geographer, and mathematician. Not much is known about his personal life, except that his surname "Ptolemaeus" indicates that he was an Egyptian descended from Greek. His first name "Claudius" shows that he held Roman citizenship. His works in astronomy are dedicated to "Syrus," who is unknown. One of his teachers was probably Theon, whom he gives credit for giving him records of planetary observations. Theon was a common Egyptian name, and this specific Theon was not the father of the mathematician Hypatia. Ptolemy had a great respect for Hipparchus and he usually treated him as if he were his only noteworthy astronomical predecessor (North, 1995).

According to historian John North (1995), "Ptolemy was *uniquely* responsible for building up astronomy from a coherent set of first principles" and "With Ptolemy, astronomy had come of age" (p. 120). The principles that he was referring to were those of Hipparchus. Expanding on the ideas of Hipparchus, Ptolemy was able to make a conjecture as to how heavenly bodies moved in space. Once he found the parameters of the models by fitting them to observation, he could predict the events that would be seen, as the results of his geometrical assumptions. In other words, where others had found patterns of repetition, Ptolemy gave reasons for these patterns (North, 1995). According to *The Cambridge Illustrated History of Astronomy*, "Few if any mathematical works of comparable quality would be written in Greek after his time" (Hoskin, 1997, p. 42).

Ptolemy's great treatise, the *Almagest*, survives today in Greek. The work is a treatise in thirteen books and is considered to be his finest work. The title of the work is an indicator of cultural movements. It began in Greek as *The Mathematical Compilation* and became *The Great* (or Greatest) *Compilation*. When the Arabs translated it in the ninth century, only the word "greatest" was kept, but in an approximation to the Greek word (*megiste*), so then it became "*al-majisti*." Then it changed to the Latin *Almagesti* or *Almagestum*, in the twentieth century, and then finally to *Almagest*, as it is known today. This work is also important because it incorporated hundreds of years of Greek science and mathematics. Ptolemy drew on Aristotle for his philosophical standpoint, Euclid for his geometrical methods, Menelaus for his spherical geometry, Eudoxus for his planetary models, and Hipparchus for his star catalogue and astronomical methods. Hipparchus' numerical methods are known because of the *Almagest* (North, 1995).

Another of Ptolemy's works, the treatise *Planisphere* (or *Planispherium*) is one of the reasons why he is given credit as being the inventor of the astrolabe. This treatise is the oldest surviving work with a thorough account of the theory of stereographic projection, which is a key mathematical principle in the creation of an astrolabe. The Greek original of the work was lost, but the Arabic translation of the work survives. Another version of the work survives from when a revision was made by an Islamic Spanish astronomer in the tenth century. The work also reached Western Europe in a Latin version in 1143 (North, 1995).

After Ptolemy's time, astronomy continued to be practiced in the eastern Roman empire of Byzantium. Synesius of Cyrene (who died between 412 and 415) was a pupil of Hypatia in Alexandria. He was a soldier who married a Christian woman and with great reluctance was convinced to accept baptism and the bishopric of Ptolemais in 410. Although he was a busy man, he somehow found time to make some improvements to the astrolabe. He presented a silver instrument of this sort to a friend in Constantinople (in Byzantium), along with a letter describing it and its uses. It is surprising that Synesius, a bishop, worked with the astrolabe because in many places the church frowned upon those who looked to the stars and practiced astrology. These people were labeled as "sinners" (North, 1995).

In another letter, Synesius claims to have been the first since Ptolemy to have written on the theory of the astrolabe projection. If this is true, then a greater work by Theon, father of Synesius' teacher Hypatia, can have only been a few years behind. Only the table of contents of this work survives, but it fits closely with a later work by Philoponos (who died about 555) and even more closely with a Syriac treatise on the same topic by the Bishop Severus Sebokht (who died in 665) (North, 1995).

Hypatia was born around AD 370 and is the first woman in mathematics of whom historians have considerable knowledge. Her father, Theon, was a notable professor of mathematics at the University of Alexandria and later became the director of the University. Theon was determined that she be the perfect human being. From early on in her life, Hypatia was deep in an environment of learning, questioning, and exploration. During this time, Alexandria was a place of great learning and was a center where scholars from all civilized countries gathered to exchange ideas. In addition to the stimulating and challenging environment, she received thorough formal training in arts, literature, science, and philosophy (Osen, 1974).

Theon was Hypatia's tutor, teacher, and closest friend. His love of the beauty and logic of mathematics was contagious and he was influential in this part of her intellectual development. During this time, it was thought that mathematics could calculate exactly where a soul would be on a future date based on what planet the soul was born under. Astronomy and astrology were thought to be one science and mathematics was what connected this science to religion. Thus in addition to being trained in the sciences, Hypatia was also introduced to all the systems of religion known to that part of the world. Theon wanted her to not only have a large amount of knowledge, but also know how to incorporate and build upon this knowledge (Osen, 1974).

Hypatia went on to become a mathematics professor at the same university that her father had made such a name for himself. She also authored several treatises on mathematics, although most were destroyed along with the Ptolemaic libraries in Alexandria or when the temple of Serapis was sacked by a mob. Only pieces of her work remain. In the fifteenth century, part of her original treatise *On the Astronomical Canon of Diophantus* was found in the Vatican library having most likely been taken there after Constantinople fell to the Turks. Hypatia also wrote commentaries on the *Almagest* and coauthored (with her father) at least one treatise on Euclid. Much of her work was prepared as textbooks for her students and as author Lynn Osen (1974) boldly states, "No further progress was made in mathematical science . . . until the work of Descartes, Newton, and Leibniz many centuries later" (p. 28).

As previously mentioned, one of Hypatia's students was Synesius of Cyrene. His letters not only indicated that he worked on the astrolabe, but also give historians one of their richest sources of information concerning Hypatia and her work. In his letters he asks for scientific advice and it is obvious how much he valued his intellectual relationship with her. There are references in his letters crediting Hypatia with the invention of an astrolabe, planisphere (another device for studying astronomy), an apparatus for distilling water, one for measuring the level of water, and another one for determining the specific gravity of liquids (called an aerometer or hydroscope) (Osen, 1974). It is probably because of these letters that many books give Hypatia credit as being the inventor of the astrolabe. The letters also suggest that she probably lectured on simple mechanics, mathematics, philosophy, and astronomy (Perl, 1978).

Hypatia belonged to a school of Greek thought called neo-Platonic, whose scientific rationalism was opposite to the unbending beliefs of the dominant Christian religion. Christian leaders felt threatened by this school and they considered Hypatia's philosophy heretical. When Cyril became the leader of Alexandria in AD 412, he started a program of oppression against those labeled as heretics. In AD 415, due to a series of events, Cyril was convinced that his own interests would be best served by the sacrifice of a virgin. Under his direction, a mob of religious extremists yanked Hypatia from her chariot while she was on her way to the university, pulled out all of her hair, and in the end tortured her to death (Osen, 1974). There are many different accounts of how Hypatia met her end, but the common thread is that she was killed at the hands of others because of her beliefs. Her death marks the end of the great age of Greek mathematics and a few hundred years later (641) Alexandria was invaded and destroyed by the Arabs (Perl, 1978). Through her tragic death, Hypatia is often labeled as a martyr and many times she is the only woman mentioned in mathematical histories (Osen, 1974).

The earliest precise description of the astrolabe comes from John Philoponus (whose work is probably derived from that of Theon), who was also from Alexandria. His manuscript dates from about 530 AD and in it he described both the construction and use of the tool. It is quite obvious that the astrolabe was well developed by the time Philoponus wrote about it. He made reference to earlier works and the model that he described is the exact model that astronomers used for years to come (Webster, 1984).

Jewish scholar, Māshā'allāh, created the Arabic text that had the most influence on European scientists. The original manuscript was written about 800 and does not survive to this day, although a Latin translation made in 1276 does. This works seems to have influenced the work of Geoffrey Chaucer on his *A Treatise on the Astrolabe* (Webster, 1984). This work will be discussed in more detail in Section IV.

The astrolabe had definitely appeared in the West by about 1025 and it is entirely possible that Gerbert of Aurillac (later Pope Sylvester II) brought from Spain knowledge of it. He lived from 945 to 1003 and was an influential scholar who visited and studied in Spain. Shortly after 1025, two Latin treatise were composed (or adapted from the Arabic) on it by Hermann the Cripple (Hermannus Contractus). He was an Austrian monk who lived from 1013-1054 (Hoskin, 1997).

The astrolabe allowed astronomy to once again become a mathematical science because with it the astronomer could measure the angle between the horizon and the position of a heavenly body. The astrolabe takes its name from the Greek word *Astro*, which means "star" and the word *Labio,* which means "taker," "finder," or "thief." So it is literally a star-finder (Webster, 1984).

At this time (the Middle Ages), there were definitely four types of astrolabe: planispheric, linear, spherical, and mariner. According to *The Cambridge Illustrated History of Astronomy*, the planispheric astrolabe was "by far the most sophisticated (and historically important) astronomical instrument of the Middle Ages" (Hoskin, 1997, p.64). The planispheric astrolabe is the typical astrolabe and usually what is meant when the word "astrolabe" is used. The linear and spherical astrolabes were and are rare. The spherical astrolabe is also known as an armillary sphere. The stars and ecliptic circle are shown on a rete that is basically a cut-out spherical shell. The shell wraps around a ball that holds the markings the climate would hold in the planispheric astrolabe. There is only one example of the spherical astrolabe known. It appeared in 1962 and is housed in the Museum of the History of Science at Oxford (Webster, 1984). The linear astrolabe was invented by Muzaffar Sharaf al-Din al-Tusi and is often called the "staff of al-Tusi." It was actually a wooden rod with graduated markings, but it did not have sights. It was capable of making angular measures. Like the spherical astrolabe, the linear astrolabe was rare and few texts even mention it in their discussion of the astrolabe. The mariner's astrolabe was a rather crude tool that was meant for use at sea and it seems as though it was developed only near the end of the Middle Ages (Hoskin, 1997). It was a bronze disc that was made heavy on purpose so that its inertia would help stabilize it at sea. It was meant for sighting only and was used to measure either the altitude of the stars above the horizon, or their zenith distance (Webster, 1984). There are several different instruments to which the name "astrolabe" has been attached at various times, but there is one kind of common plane astrolabe (the planispheric) that far outnumbers the rest (North, 1995).

The mechanical clock is documented with certainty from the fourteenth century, but it is possible that it originated in England in the late thirteenth century. It emerged as a highly complex and sophisticated instrument. Because telling time came from astronomy, it is not surprising that the more refined clocks were astronomical. Some of these clocks were even mechanical astrolabes (Hoskin, 1997). As with the astrolabe, the mechanical clock was a direct result of a longing to represent the moving heavens in a concrete form. Although the astrolabe was not an instrument that the ordinary person was able to attain, it was known to very many because on a grand scale it was the front of the astronomical mechanical clocks. Considering the astrolabe's Vitruvian ancestry, it is fitting that it was the prototype clock face (North, 1995).

Water clocks from fourteenth century Fes, Morocco included astrolabe dials. It is not known if western European knowledge was being brought back into Islamic northern Africa at this time, but it is definite that by the time the clock in Fes was set up in the Qarawiyyin Mosque the European astrolabe clock with a mechanical drive was not uncommon. Again, this invention was a direct product of the desire to represent the moving cosmos (North, 1995).

Near the end of the Middle Ages there was a "rebirth" of the sciences and specifically astronomy. This can be attributed to the impact of the invention of printing (1450) and the Spanish and Portuguese voyages of exploration that resulted in the discovery of America in 1492. The expeditions of Columbus or Vasco da Gama would not have been possible without the compass or the elements of mathematics and astronomy that allowed them to measure longitude and take bearings at sea. Astronomy also benefited from these voyages because it could no longer be denied that the earth was round (Reichen, 1968).

The identity of the oldest surviving portable astrolabe is a matter of disagreement. From eastern Islam there exists an early copy of a ninth century example and there is a dated original from about AD 928 (North, 1995). There are also preserved astrolabes in Oxford that date back to the tenth century (Chapman, 1995). The astrolabe reached its maturity in Islam and actually retained its popularity into modern times (Hoskin, 1997). There is a Persian example dated at the year 374 of the Hejira (AD 984) and bears witness to a long craft tradition. This confirms what is known from eighth century literary references from Baghdad and Damascus. Within a few centuries there are examples of texts and devices coming from every important center of civilization between India and the Atlantic. Persian craftsmanship was high quality and was rivaled in Europe only in the sixteenth and seventeenth centuries (North, 1995).

Although Ptolemy's treatise, *Planisphere*, was popular, it was not the sort that could have ever made the astrolabe popular. In the later Islamic and Christian worlds, many alternative texts were produced. The European writings were numerous, but they came from only three main families and all three families came from Muslim Spain (North, 1995).

There was no other scientific instrument of comparable importance, artistically or symbolically, in any of the major cities. Well into the seventeenth century, in the east and west, the astrolabe remained a working tool of the astronomer and a powerful symbol. It symbolized not only the cosmos, but astronomy itself. It was known by sight to many who had no understanding at all of its many workings. It was also a concrete reminder of the Greek brilliance for combining astronomy with geometry. When Corpus Christi College (a University of Oxford) was founded in 1517, arrangements were made so that astronomy would be taught there. There was no qualified humanist for the job, so they hired Nicolaus Kratzer (1487-1550). He was a popular astronomer and mathematician at the time. In a letter from a pupil, Kratzer was described as a "skilled mathematician, bringing with his astrolabes and armillary spheres and a Greek book" (North, 1995, p. 274). Astrolabes, armillaries, and globes had become the symbols of the astronomer and common parts of the instrument maker's inventory (North, 1995).

The National Museum of American History has a collection of astrolabes that reflects a long-standing American interest in the subject. The first astrolabe purchased for the United States National Museum was in England by American Samuel P. Langley in 1888. He purchased this astrolabe as well as several other scientific instruments from Raoul Heilbrunner. The museum's astrolabes that were to follow came from a variety of owners that represented a range of economic classes. These owners had acquired the astrolabes in the nineteenth and twentieth centuries as either a single piece of curiosity or in the process of building a collection. Some of these owners were recent immigrants, while others were Americans of colonial ancestry. A large number of the astrolabes in the National Museum of American History belonged to the Samuel V. Hoffman collection and are now in the Smithsonian Institution. The collection of astrolabes at the National Museum of American History is the fourth-largest museum collection in the world (as of 1984). The three largest collections can be found at the Museum of the History of Science in Oxford, the Greenwich Maritime Museum, and the Adler Planetarium in Chicago (Gibbs & Saliba, 1984).

Mathematics and Construction

In order to create an astrolabe, the maker needs to transfer the sky onto a sheet of brass. From geometry it is possible to set up a projection between the points in the celestial sphere and the points on a plane, so that each point on the sphere is matched to exactly one point on the plane. One way to do this is to imagine a line joining the celestial South Pole to any other celestial point and take the projection of the point to be where this line meets the plane that contains the celestial equator. This type of projection, known as stereographic projection, has the important and unexpected property that angles between curves on the heavenly sphere are unchanged after projection. This is helpful because problems involving spherical triangles can be converted into more workable problems in plane trigonometry (Hoskin, 1997). Stereographic projection is also important because of its impact on the design of astronomical instruments (North, 1995).

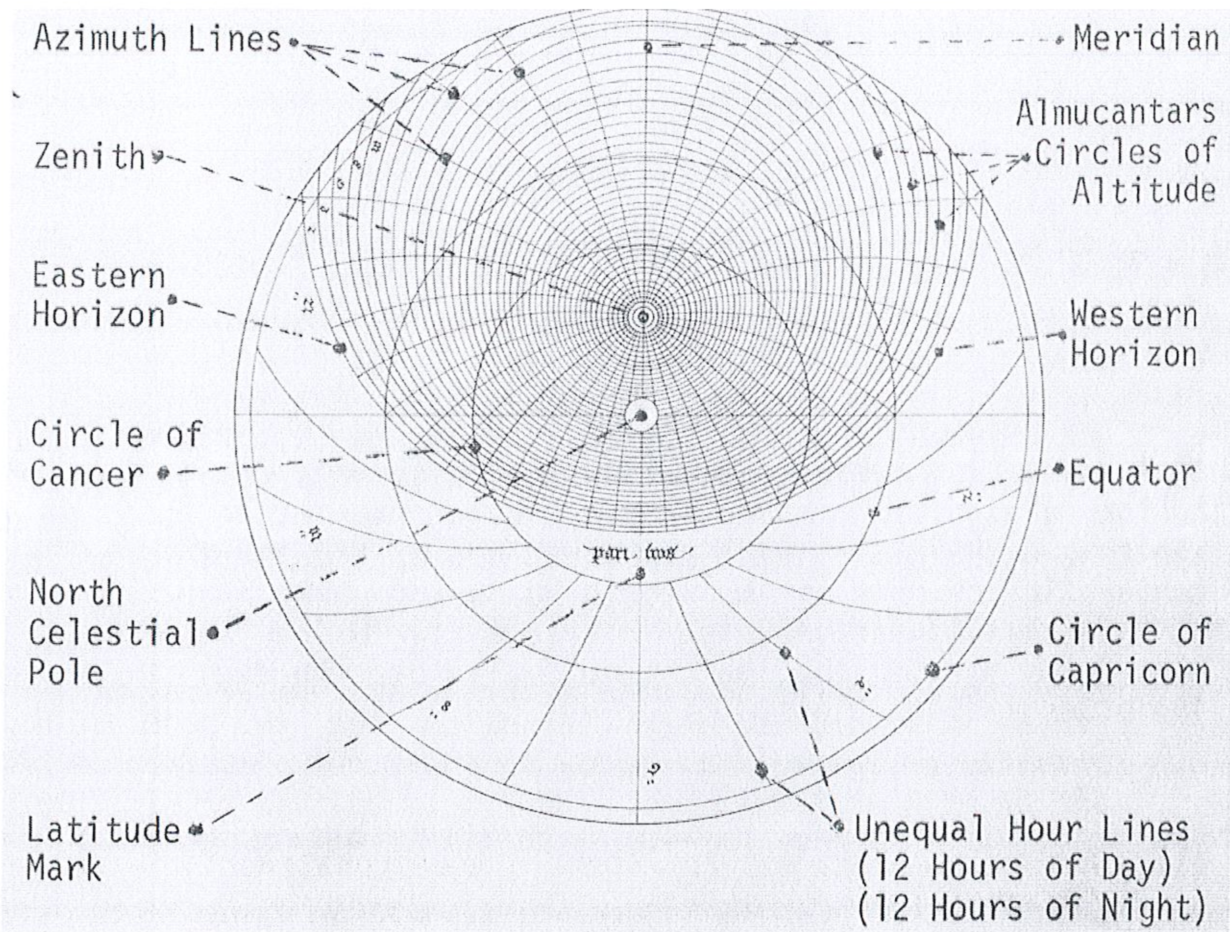
Another way to visualize stereographic projection is by thinking of the network of circles that make up the celestial sphere to be made of wire. If the sphere sits on a plane sheet, touching at one of the poles, and a bright source of light is shined at the other pole, then the shadows of the wires on the sheet will be in stereographic projection. If the sheet were to be in the equatorial plane then the same diagram would result, but it would be at half the scale. This is why stereographic projection is at times described as a projection from a pole onto an equatorial plane. Again, this type of projection is useful because circles project into circles and angles on the sphere project into equal angles on the plane (North, 1995).

To understand the astrolabe, one needs to consider a few things. Upon observation, one would notice that the stars, equator, ecliptic, and other circles on the celestial sphere all move around the pole with a daily rotation. It is necessary to distinguish these circles from another set, a fixed set, which makes it possible to specify the positions of objects in the heavens. These fixed lines are the local horizon, meridian line, and other lines determined by the astronomer. It is customary to imagine a line drawn around the sky 1° above horizon, another at an altitude of 5°, and continuing up to the zenith overhead, at 90° above horizon. The astronomer could draw in additional lines for the purpose of locating the bearings of stars in the azimuth. Astronomers often built a three-dimensional model of this double system and called it an "armillary sphere." This sphere could be used for many astronomical purposes because it was no more than a diagram in three dimensions. Basically, it was a representation of angles, but not of distances (North, 1995).

Returning to the wire model, the network of fixed lines could be represented by a wire mesh. The trick here is distinguishing the representation of the fixed lines from that of the moving lines. The shadow of the moving mesh would rotate, but the shadow of the mesh of the local coordinates would not. Adding the two sets of lines to the representation is how the astrolabe would be understood (North, 1995).

The brass disc that makes up the astrolabe is a physical replica of the plane through the celestial equator, onto which the celestial sphere has been projected (or represented). The limitation with the disc is that it is limited in size, the portable version of the astrolabe was usually between ten and twenty centimeters across (although there are plenty of smaller and larger examples) (North, 1995). Because the astrolabe is not very big, not all of the celestial sphere can be represented on it. No harm was done if the southern skies were left unrepresented. The Muslim and Christian users never saw the skies near the celestial South Pole. This was the reason why they picked the South Pole as the center of the projection (Hoskin, 1997).

If the South Pole is chosen as the center of the projection, then the representation of the North Pole would be at the center of the disc so that the moving part can pivot around it. Around the North Pole there would be three concentric circles that represent the Tropic of Cancer, the equator, and the Tropic of Capricorn. The Tropic of Capricorn is the outer limit of the disc and the skies that are south of the line are not represented (Hoskin, 1997). The plane that the circles are projected onto is any plane parallel to the equator (North, 1995).



(Webster, 1984, p. 10)

Observations that are made with the alidade are of the angular altitudes of the heavenly bodies. These angles are within a coordinate system where the horizon is $0°$ and the zenith is $90°$. For the convenience of the user, circles of equal altitudes ($0°, 10°,$ up to $90°$) must be represented in the projection, along with circles of equal azimuth. The horizon circle intersects the equator at two absolutely opposite points. The parallels of equal altitude converge toward a point which is the image of the zenith (Neugebauer, "The Early History," 1983). These circles, called "almucantars" (from an Arabic word), would not be centered at the poles, but they would still be circles and not ellipses (North, 1995).

The problem with this is that these circles, and thus their projections, depend on the latitude of the location of the observer. The solution to this problem was to equip the astrolabe with discs for a range of latitudes. Each disc, called a climate or tympan, was engraved with the projection of the appropriate coordinate circles, the most important of which is the horizon. The climates were stored in a shallow tray, called the "mother," with one on top of the other so that the user could simply select the most appropriate one and put it at the top of the pile (Hoskin, 1997). There were some astrolabes that were intended to be used at any location, with only one climate, but they were difficult to use and very few were made (North, 1995).

Below the horizon is another set of curves that represent the seasonal hours for a given latitude (see previous diagram). The sixth curve is a straight line that passes through the center of the astrolabe and represents the meridian. To find these hour curves, draw a circle with the North Pole as the center and divide the arc below the horizon into twelve sections of equal length. This will give eleven dividing points if the endpoints on the horizon are not counted. When the sun travels on a given circle (that is parallel to the equator), the dividing points represent the seasonal hours of night for the given day (Neugebauer, "The Early History," 1983).

All of the features mentioned so far are static and fixed. It is necessary to project individual stars of the heavenly sphere and since the heavens rotate, it is essential that the projection rotates. If transparent plastic had been available in the Middle Ages, it is quite possible that the projected stars would have been engraved onto a plastic disc that could rotate about the central point. Looking through the plastic, the user could have seen the coordinate circles engraved on the climate below (Hoskin, 1997).

Since transparent plastic was not an option, the maker took another disc of brass (see Appendix), the rete (which means "a net" in Latin), and on it they marked the projections of important moving features of the sky, making a sort of "star map." These features include the ecliptic path of the sun (the most obvious circle on the rete), the positions of the principle stars, and the signs of the zodiac. The maker then cut away the rest of the brass, as much as possible, and kept only the important features, exposing the climate below and its coordinate grid. The stars were represented by pointers and the endpoints actually corresponded to the projections of the stars. The moving ecliptic, which leans to the equator, is not centered on the poles, but would still be projected as a circle and not an ellipse (Hoskin, 1997).

It is not necessary that the rete represents the star sphere and the climate hold the horizon, meridian, etc., but rather the relative motion of the rete and climate is what is important. Letting the rete hold the stars became the almost universal practice, although the roles could be reversed. An example of this can be found in Vitruvius' anaphoric clock (North, 1995).

A single observation fact is all that is needed to locate all of the stars in the positions that they are in at the time of the observation because the heavenly sphere has only 1° of freedom even though the heavens spin. For example, if an astronomer used the back of the astrolabe to measure the altitude of Sirius (and knows if it is rising or setting) it would be possible to go back inside and rotate the rete until the representation of Sirius is located over the corresponding altitude circle in the coordinate grid. Now, not only Sirius is located, but also all of the other stars as well. It is possible to determine the current positions, which stars are about to rise, and which stars have just set (North, 1995).

Composition and Applications

The basis of the astrolabe is a disc of brass that can be hung from a ring. They were usually made by astronomers for their own use, although some were made for patrons and wealthy men. These were richly ornamented and exquisitely engraved. Other than superficial changes in style and artistry, astrolabes changed very little over the centuries (North, 1995). However, it is possible to distinguish an Arabic astrolabe from one of European descent by the scales and tables on the back as well as the inscription on the front rim (Gibbs & Saliba, 1984).

The back of the disc is essentially an observing instrument. The alidade (see Appendix) is fitted to the back and it rotates around a pin in the center of the disc. The alidade is used to measure the altitude of celestial bodies. The observer holds the instrument from the ring so that it hangs vertically and looks along the alidade toward the object in question. The altitude of the object is read from a scale that is engraved around the circumference of the disc. The western astrolabe also has two circular scales on the back which together give the position of the sun on the ecliptic for any date in the year. One of the rings is engraved with the days of the year, while the other gives the corresponding position of the sun. There is also a ring divided into twelve sections by the signs of the zodiac. The alidade can be used to line up the corresponding parts (Hoskin, 1997).

The front of the astrolabe is a calculating device that has representations of both the heavens (including individual stars, ecliptic, equator, and tropics) on the rete and of the local system of coordinates (including angular altitude above the horizon and angle of azimuth around the horizon) on the climate (see Appendix). The observer uses the rete and the climate together to make measurements of the positions of the heavenly bodies. Some astrolabes also have a rule (see Appendix), without sights, that lays on the very top of the instrument (Hoskin, 1997).

The way the astrolabe was put together was because it was meant to be used for observation as well as computation. This was the reason for a ring and shackle at the top of the astrolabe. The instrument could be hung vertically from the thumb of one hand, while observations were made with the help of the alidade on the back (North, 1995). Further observational aid was added on medieval European astrolabes for the ease of the user. The aid was a shadow square (see Appendix) that provided a graphic solution to problems involving tangents and cotangents (Webster, 1984).

There are numerous uses for the astrolabe and a typical text will explain over forty. Many of the uses require the moving rete to be positioned correctly, by reference to the observed altitude of a star, in relation to the fixed climate. The rete is rotated around until the star's marker lands on the correct almucantar on the climate below (North, 1995). Many of uses of the astrolabe listed in Chaucer's *A Treatise on the Astrolabe* (Skeat, 1900) involve just this. The problem with most of Chaucer's directions is that they are out of date. For example, in Chaucer's time the first degree of Aries answered to the twelfth of March, but in the 1900's it was between the twentieth and twenty-first of that month. That difference of about eight days needed to be accounted for when making calculations.

The primary use of the astrolabe was to find star positions. The first step in using the astrolabe is to measure the altitude of a star above the horizon. This can be done by holding the instrument by a cord or ring and sighting the star through the small holes in the alidade on the back of the astrolabe. Then read the angle from the rim of the astrolabe at the end of the alidade. Write down the angle and return inside to make the necessary calculations, using the rete and tympans (climates) on the front of the astrolabe (Webster, 1984).

Suppose that Arcturus was the star that was sighted and it was found to be at thirty degrees above the eastern horizon. Select the appropriate tympan for the latitude where the observation was made and put it at the top of the pile, directly under the rete. It is not likely that there will be a tympan that will correspond exactly with the latitude of the observation, but the tympan that is the closest should be chosen. Turn the rete until the tip of the star pointer (that represents Arcturus) lands on the almucantar marking the altitude of thirty degrees above the eastern horizon. The astrolabe is now set to show the positions of all of the other stars at the time of the original observation as well as the solutions to a large amount of problems that may be solved with the tool (Webster, 1984).

One of the basic uses of the astrolabe was to tell time. The astrolabe can tell both stellar (star) time and solar (sun) time. In other words, the astrolabe was a twenty-four-hour clock that made it possible to tell time from a single observation of the sun in the day-time or of a star at night (Hoskin, 1997). To determine stellar time, leave the rete in its original setting as found when locating star positions. Turn the rule (that lies over the rete) until it is over the first point of Aries. This point is marked on the ecliptic circle. The time on the hour circle, on the rim of the astrolabe, will be indicated by the end of the rule. Since the astrolabe is only marked to twelve and stellar time is on a twenty-four hour basis, personal judgment should be used to determine if twelve should be added to the hour indicated. Because the basic measurement is the angular distance of the first point of Aries from the meridian, it should not be difficult to determine (Webster, 1984). Only western astrolabes have a rule on them, so the Islamic astronomers were only able to tell time during daylight hours (Hoskin, 1997).

In order to find solar time using the star positions, another step is needed. On the back of the astrolabe is a double calendar scale. It is possible to line up the alidade with the correct date on the month scale and find the corresponding position on the zodiac scale. This indicates the sun's location in the ecliptic circle for that day. Going back to the front of the astrolabe, the rule must be set to the sun's position in the ecliptic circle. It is important that the rete is not allowed to move from its original setting. The end of the rule will mark solar time on the rim of the astrolabe (Webster, 1984).

It is also possible to tell time by using the sun with about as much ease as with the stars. First note the position of the sun in the ecliptic. Then mark (using a pencil) the appropriate place on the ecliptic circle. Measure the altitude of the sun and position the rete so that the mark reaches the correct almucantar. The time can be read the exact same way as if it were measured from a star (Webster, 1984).

Another use of the astrolabe was to predict the time when an astronomical event would happen. For example, an astronomer wanted to know the hour when the sun would rise. Once the place of the sun in the ecliptic has been marked, it is fairly simple to find the sunrise and sunset for the day in question. Move the mark of the sun's position so that it is over the eastern (for sunrise) or western (for sunset) horizon. Line up the rule with the mark and read the hour from the rim of the astrolabe. Finding the rising and setting of a star can be done in basically the same way. To find the hour in which a star will rise, set the tip of the star pointer to the horizon. Line up the rule to the place of the sun in the ecliptic circle and read the hour on the rim of the astrolabe (Webster, 1984).

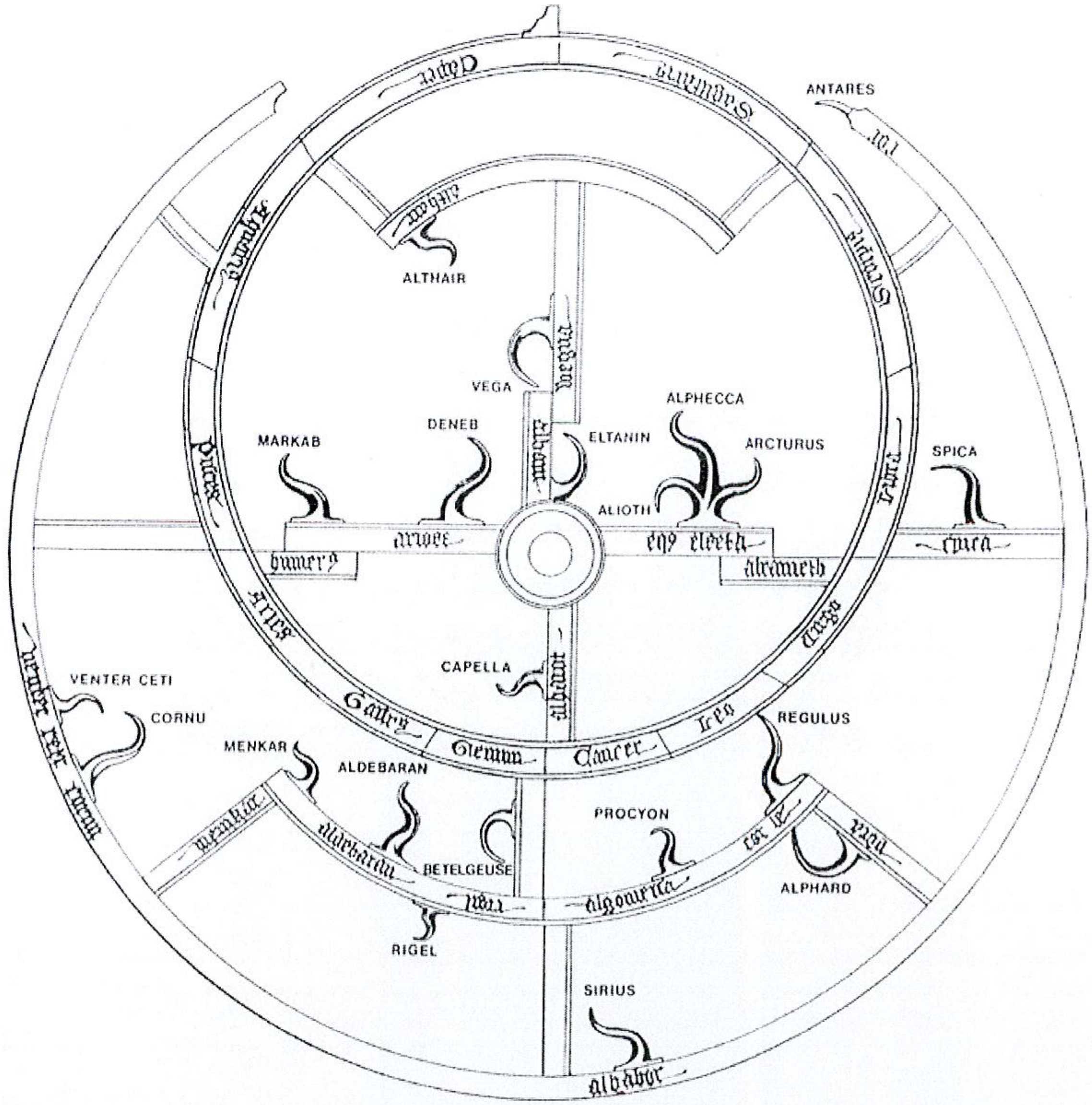
It is also possible to locate the positions of the moon and planets with the aid of an almanac. "The Nautical Almanac" gives the Greenwich Hour Angle (G.H.A.) for the first point of Aries, the planets, the sun, and the moon for each hour of the year. To find the moon or a planet in the ecliptic circle there are a few steps to follow. First look up the G.H.A. of the planet for the day and hour. Subtract the G.H.A. of Aries from the G.H.A. of the planet, resulting in the Sidereal Hour Angle, S.H.A., of the planet (thus G.H.A. planet – G.H.A. Aries = S.H.A. planet). Then set the rete so that the first point of Aries is in line with one of the zero degree points on the rim of the astrolabe. In a clockwise direction, measure the S.H.A. of the planet in degrees. Finally set the rule to this point and mark the position on the outer edge of the ecliptic circle on the rete. Another almanac that can be used for planetary positions is "The American Ephemeris." In this almanac, the right ascension of the planet is given. This is measured in hours and minutes from the first point of Aries. It would be counted off in a counterclockwise direction on the astrolabe (Webster, 1984).

The astrolabe helped present an intellectual challenge, allowing astrology to take on a life of its own, and it was not just a way of making money or gaining power. In the case of determining planetary positions for astrological purposes, the total time and energy involved prove the seriousness of the astrologer (North, 1995). The signs of the zodiac, which are important to astrology, represent the twelve constellations that divide the ecliptic into twelve sections of equal length. If the sun is said to be in Pisces it is being described as being in a certain position on the ecliptic. This position denotes the season of the year. In astrology that was more developed, the signs of the zodiac affected the moods and fates of living creatures on the earth (Reichen, 1968).

One of the tasks of astrologers was to note the positions of the signs of the zodiac in the "houses of life." These houses were twelve unequal intervals through which the signs of the zodiac passed in their journey from the nadir to the zenith. Along with the positions of the signs of the zodiac, the astrologer would note the characteristics of the planets and their positions within the signs of the zodiac in order to cast horoscopes. While this may seem like a childish game today, medieval astrologers contributed greatly to the development of true astronomy. It was hard to tell the difference between an astronomer and an astrologer because the instruments they used were the same (the astrolabe, the armillary sphere, the quadrant, and the compass). Also, in trying to divine the destinies of humans, the astrologer observed the skies and gained a more thorough knowledge of the earth (Reichen, 1968).

The astrolabe could make the astronomer's life easier even though it was not exact enough for the perfectionist. It really was of no great value as a device for exact observation and when it came to computation it was usually too small to give more than an approximation for complex problems (North, 1995). The care with which it was fitted with a means of suspension determined the quality of the astrolabe as an observational instrument (Gibbs & Saliba, 1984). Astronomers were aware of the low accuracy of their instruments. Astronomers were able to use mathematical theory to compensate for the astrolabe's shortcomings in accuracy (Neugebauer, "Mathematical Methods," 1983).

A problem that needed careful attention was dividing the ecliptic circle on the rete (see diagram on the following page). Since the plane of the ecliptic is tipped in relation to the plane of the equator, the divisions would not be uniform. The correct procedure would be to start at the point of Aries and divide the circle of the equator uniformly in $1°$, $2°$ or $5°$ units. The next step would be to lay a rule from the pole of the ecliptic to one of the marks on the circle of the equator. Then mark where the rule crosses the ecliptic circle. Every thirty degrees on the equator will denote the divisions between the signs of the zodiac on the ecliptic circles (Webster, 1984).



In his book, *Dividing the Circle* (1995), Dr. Chapman discusses not only the historical importance of astronomical instruments, but also the concept of accuracy in the development of astronomy over the period of 1500-1850. For one of his studies, Dr. Chapman selected twelve astrolabes from the collection in the Museum of the History of Science, Oxford. The astrolabes in his selection were engraved in Europe, were dated from about 1450 to 1659, and were between six and sixteen inches in diameter. The selection was made based on the state of preservation and the "visual fineness" of engraving.

The instruments were placed on a modern engineer's dividing engine that was equipped with micrometer scales reading down to one second. The engine had a twelve inch plate, or table, and a low-powered microscope was fitted above the plate. The microscope was fitted with cross-wires and was meant to provide a pointer against which the astrolabe scales could be read. The dividing engine's zero degree point was adjusted so that it would line up with the individual astrolabe's zero and the scale was rotated until the first degree line appeared. The position was noted as well as its deviation from a perfect degree. Each of the remaining degrees was measured the same way and a table of errors was constructed for all 360 degrees of the instrument. The spread of errors was plotted on a graph and a computer analysis established the overall mean graduation error of the scale.

From their results they were able to tell if errors were random or if there were patterns that indicated construction techniques. One of the error patterns they found indicates that the craftsman graduated one half of the circle by compass division and then copy-divided the opposite half. This was probably done using a straight edge and transcribing the original divisions. Another error suggested the maker used some sort of master template or protractor and copied it off onto the circle. This produced the same errors in each of the quadrants. These two methods suggest that labor-saving techniques were used and imply the use of commercial methods of production.

Another discovery of this investigation was the wide range of accuracies among the samples. Some scales were quite consistent, with an average deviation as low as 0.48 minutes. Other scales did not fare as well and had deviations as great as eight or nine minutes. Although it may seem like a large range of accuracies, it is necessary to take into account the sizes of the astrolabes. It is much more difficult to divide a six inch as opposed to a sixteen inch radius circle. There is a certain "clumsiness factor" that must be taken into account and the accuracy does not always reflect the skill of an individual graduator. One thing that became clear during this study was the lack of improvement in accuracy of the 200-year range of instruments that were examined. The later astrolabes were not significantly superior to the astrolabe of 1450. Dr. Chapman (1995) interpreted this as the "growth of a conservative craft to meet the demands of a stable market of satisfied customers" (p. 155).

The Astrolabe as a Teaching Tool

Even with its technical flaws, as a teaching device and for clarifying problems in positional astronomy, the astrolabe has had few rivals (North, 1995). One of the more famous writers to cover the topic of the astrolabe was Geoffrey Chaucer (1343-1400) who is best known for *The Canterbury Tales*. It was thought that he wrote a *Treatise on the Astrolabe* for his son, although it is more likely that he wrote it for the son of a friend, Lewis Clifford. Chaucer did not finish the work, presumably because Lewis Clifford died in 1391. The work was eventually finished by other sources, but the beginning is Chaucer's own. The work is the oldest technical manual in the English language and indicates that Chaucer was well educated in science in addition to his literary talents ("Treatise," 2005).

The beginning of the treatise gives a solid idea of Chaucer's goal. The original work was written in old English and starts:

> Lyte Lowys my sone, I aperceyve wel by certeyne evydences thyn abilite to lerne sciences touching nombres and proporciouns; and as wel considre I thy besy praier in special to lerne the tretys of the Astrelabie. Than for as moche as a philosofre saith, "he wrappith him in his frend, that condescendith to the rightfulle praiers of his frend," therfore have I yeven the a suffisant Astrolabie as for oure orizonte, compowned after the latitude of Oxenforde; upon which, by mediacioun of this litel tretys, I purpose to teche the a certein nombre of conclusions aperteynyng to the same instrument. ("Treatise," 2005).

Translated into modern English:

> Little Lewis my son, certain evidence enables me to well perceive your ability to learn the sciences, including numbers and proportions; and I have also heard your constant

> requests to learn of the astrolabe in particular. And, since the philosophers say "He who grants the reasonable requests of his friend joins himself to that friend", I have given you an astrolabe designed for our horizons and calibrated to the latitude of Oxford; with which, according to the information in this little treatise, I propose to teach you a certain number of conclusions appertaining to the instrument. ("Treatise," 2005).

He also lays out five topics that he intends to cover in the work. The first part was a description of the astrolabe. The second part was directions on how to use the instrument. These two parts were all that he was able to finish. The other three include tables of longitude, latitude, declination, etc, a theory of the motion of celestial bodies, and an introduction to the broader field of "astrologie." This word refers to what has since been broken into astronomy and astrology. The work has been praised for its ability to explain difficult concepts in a way that the reader can understand. Since the astrolabe is not commonly used, it has become difficult for the readers of today to understand ("Treatise," 2005).

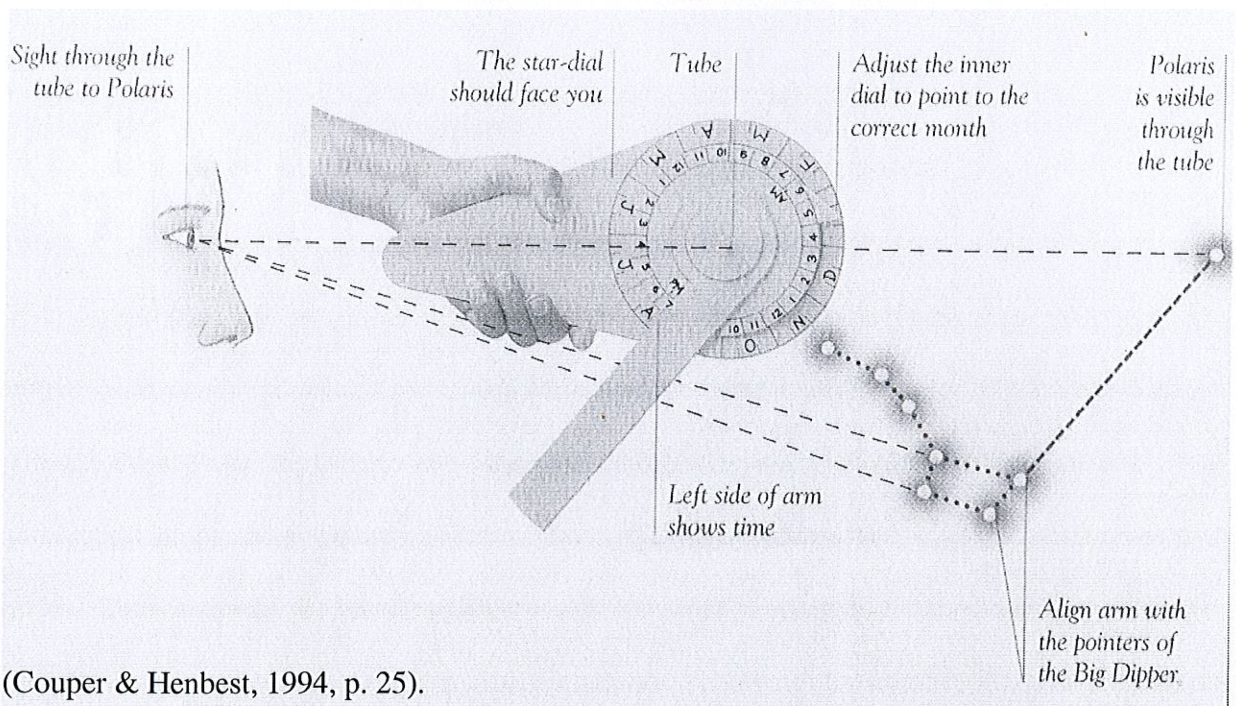
Although some of the concepts behind the astrolabe are difficult, it is possible to bring the astrolabe into the classroom. Because of its long and interesting history, it is possible to discuss the astrolabe and its travels through time in a history class. It would be a way to interest students who are normally more inclined to math and science courses. The history could also be discussed in the mathematics classroom as a way to interest students who are normally interested in the social sciences. In an art class the intricate design of the astrolabe could be discussed, as well as the numerous paintings that feature either an astronomer using an astrolabe or astrolabes hanging on the wall in the background of the picture. The social impact of the astrolabe (and astronomy in general) could be explored in a sociology class, as well as a history class. Usually there is a year (or at least a unit) of middle school science devoted to astronomy and it would be fairly easy to include a lesson on the astrolabe. Chaucer's *Treatise on the Astrolabe* could be a featured work in an advanced placement English class in place of *The Canterbury Tales,* either as an extension or a substitution. I feel that there are few courses that would be unable to incorporate the astrolabe into their curriculum.

If the school were anywhere near Chicago, it would be worth the time to take a field trip to Adler Planetarium just to see their collection of astrolabes and other scientific instruments. They have about 1600 pieces (one of the third largest collections in the world) in their "Universe In Your Hands" exhibition, which opened in the spring of 1995. The exhibition uses the artifacts to give visitors a chance to explore concepts, people, history, and science, including the practical applications of astronomy through the ages. Each artifact can be considered an icon for the social order, beliefs, and customs of the time of its creation (Webster, 1998). For students to see a collection so large that is only rivaled by collections in Oxford, England or Florence, Italy, could be a powerful experience. It is one thing to learn about artifacts, but it is completely different to be able to see and practically touch something that is hundreds of years old.

It is possible to find astrolabe templates, from a variety of sources on the internet, that can be printed and used in almost any level mathematics classroom. A real astrolabe can range in price from a few hundred dollars to several thousand, so it is not practical to have an actual astrolabe in the classroom. Although the students may not be able to sight stars in class, they can certainly sight stars that are placed on the ceiling. They can go through the process of lining up the alidade and then the rete to find the star positions. The teacher would position the stars and know what the students should find during their observations. The students would also be able to go outside and sight the sun. This activity has many possible adaptations and the level of difficulty could range from simply following step-by-step directions, to completing the activity independently with little direction from the teacher.

There are also online sources that host astrolabe "software." This software allows you to input your coordinates and it completes the computations. While there would not be much work involved for the students, it would be a good example of how far the astrolabe has come and how people are still interested in topics that were popular hundreds of years ago. This would also be a free activity for the students, where some other activities may involve some cost to the school.

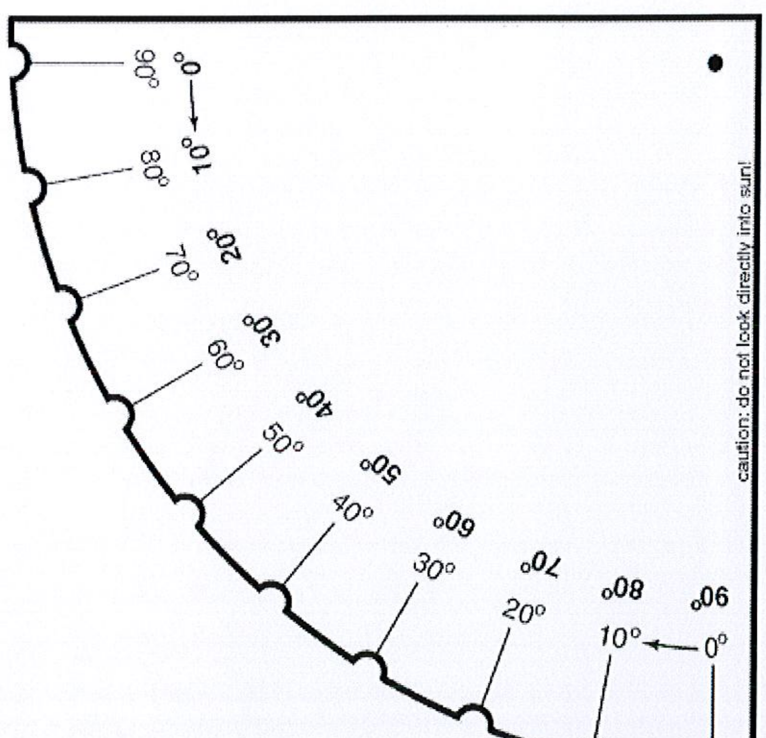
Another activity that is based on the astrolabe is making a star-dial and can be done with students at almost any level. The specifics for the activity can be found in *How the Universe Works* (Couper & Henbest, 1994, p. 25).



(Couper & Henbest, 1994, p. 25).

The star-dial is an instrument that shows the correct time when it is adjusted to the correct date and pointed at the star Polaris. This is one of the functions of the astrolabe, although the procedure is a little different. There are two dials on the star-dial. The outer dial has the months marked on it, while the inner dial has times and a pointer. The inner dial is adjusted so that the pointer is over the correct month. Polaris is sighted through the tube in the center of the star-dial while the arm of the star-dial is kept parallel to the pointers of the Big Dipper. The point where the arm crosses the inner dial is the time.

<u>*How the Universe Works*</u> (Couper & Henbest, 1994), also has an activity to find the latitude of the user. This is done by creating a quarter-circle that is similar to an ancient quadrant. The edge of the instrument is marked in degrees ranging from zero to ninety. A sighting tube is hinged to the tool. The user locates Polaris through the tube and reads off his or her latitude from the scale. This is also the altitude of Polaris, which could be found using the astrolabe. This activity is fairly simple, inexpensive to create, and yet it still gives the students an experience that is similar to using an astrolabe.



("Activity 7," 2001)

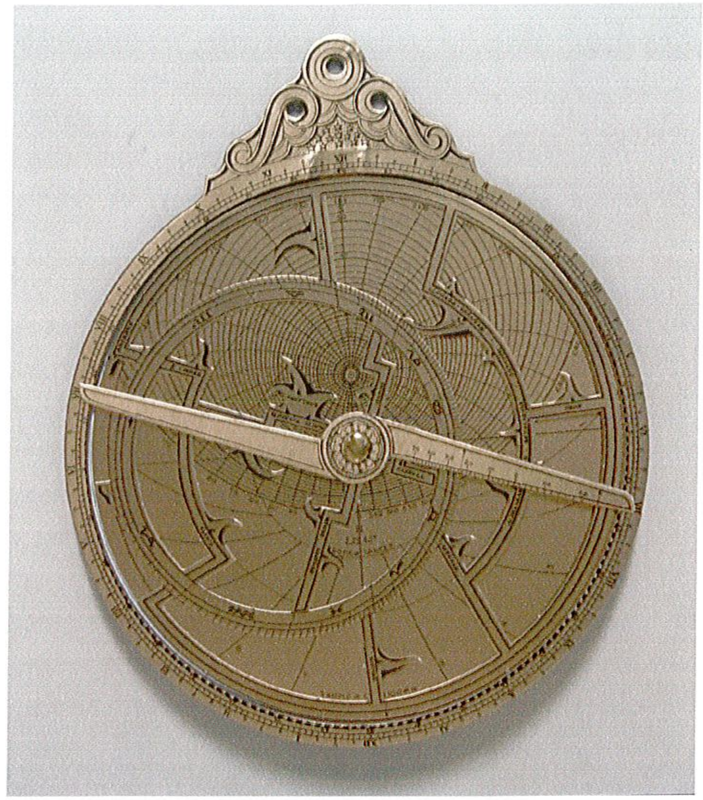
This is an activity that I could see myself using in a middle school classroom, with some modifications. I plan to teach somewhere in Minnesota, where Polaris is visible in the sky. I would spend a period with the students constructing the quadrant and pointing out some of the connections to the astrolabe. I would instruct them to take their "astrolabes" home and determine their own latitude. The following day in class we would collect the data and discuss the results. The remainder of the class period would be spent on a GPS activity found on Nova's website (http://www.pbs.org/wgbh/nova/shackletonexped/navigate/gps.html). This site features an interactive explanation of how the GPS works. In this day and age, most students have heard of GPS and possibly even have parents who own one. I think this activity would be interesting to students and something that they could share with their parents. It would be a solid example of math and science being used in a context that they are familiar with. Often, young people are fascinated with technology so this activity would probably be of interest to most students. And although it is not likely that middle school students would have their own GPS, the astrolabe is something that would provide much of the same information and is something that students would have access to after this lesson.

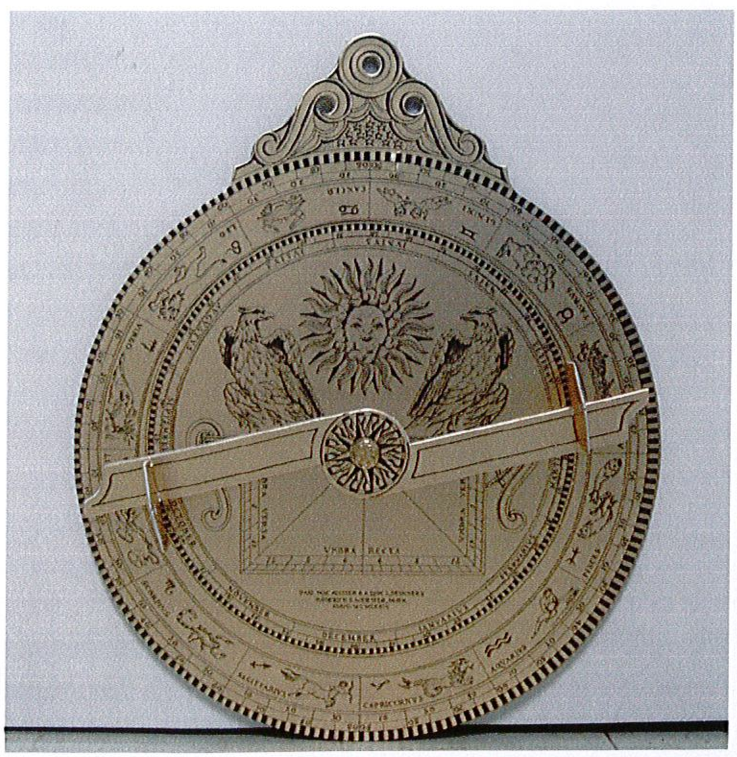
Another area where I would personally include a lesson on the astrolabe would be an upper level mathematics class in a high school. The astrolabe is often referred to as an early computer and it is likely that students in upper level mathematics are interested in careers in mathematics, science, or technology. Spending some time exploring the astrolabe and its properties would be a way for students to apply some of the concepts they have learned. They would have a "hands-on" way to use their knowledge in an approach that they are not accustomed to. It is my experience that advanced students are often given less hands-on activities and more work on paper. It would be a nice break from what they are accustomed to and way to experience mathematics in practice.

Although the astrolabe is an instrument of the past, it is possible to bring it into the present and make it a part of the future in more students' lives. It is important that students have meaningful experiences during their education, and I believe that working with the astrolabe could be one of those experiences. Since the astrolabe spans a variety of subject areas, it can be discussed in almost every secondary classroom. The more a student works with the astrolabe, the more likely it will become a memorable and (hopefully) meaningful experience. There are a variety of free sources that make it possible for any student to learn about this instrument that was a major factor in shaping the field of astronomy. And while the astrolabe is not something that students will likely see in their everyday life, stars are something that most will.

Appendix: The Parts of the Astrolabe

The Front of the Astrolabe

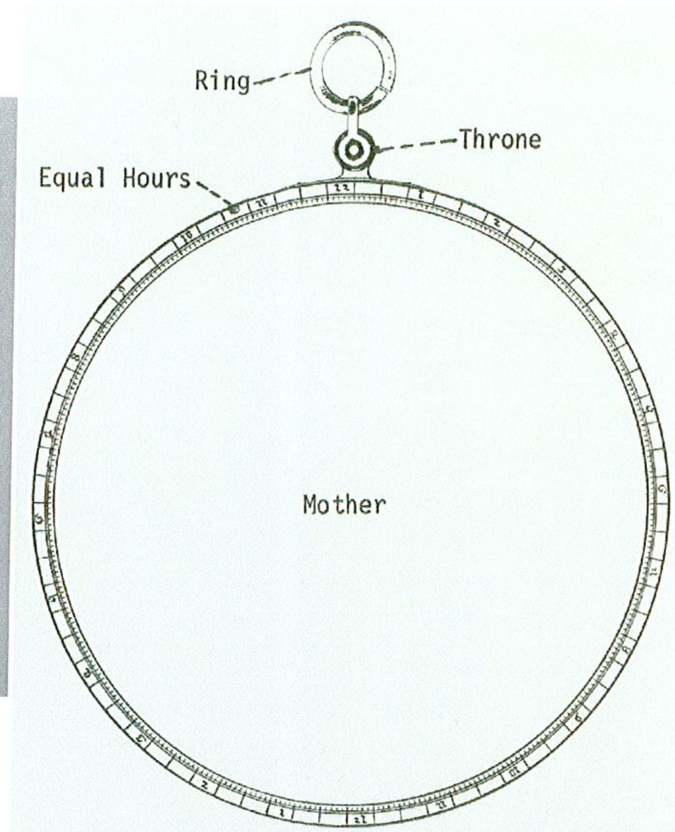




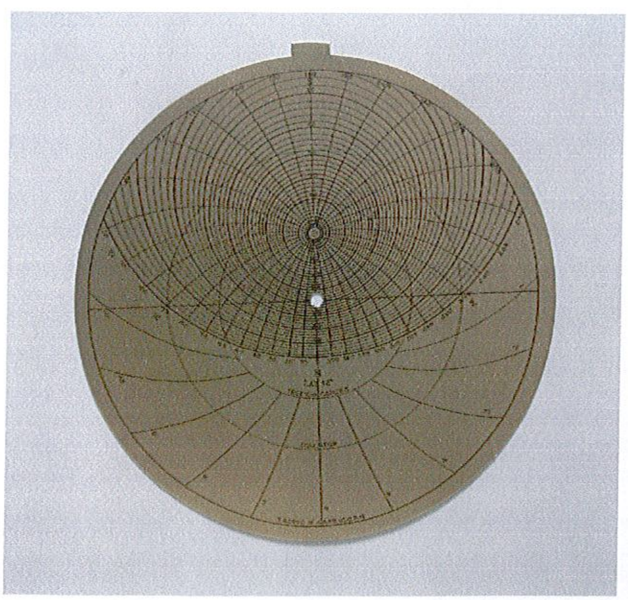
The Back of the Astrolabe

The Mother

The mother is hollowed out to hold the rete as well as several tympans. A scale of hours is engraved on the rim. On a standard astrolabe, a shackle and ring are provided to hold the mother.



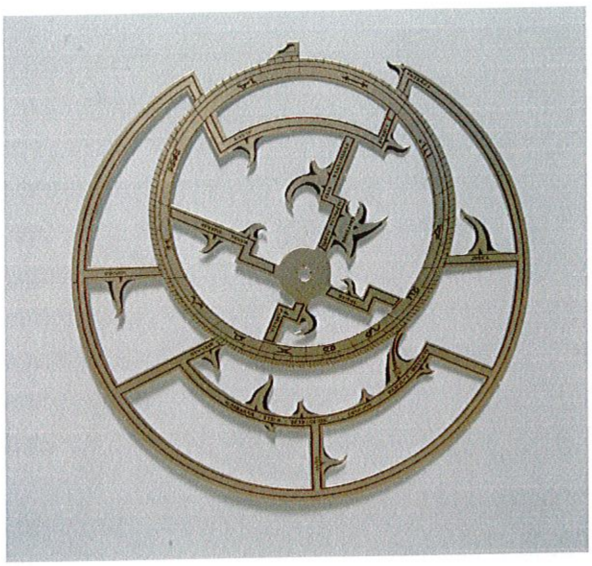
(Webster, 1984, p. 10)



The Tympan

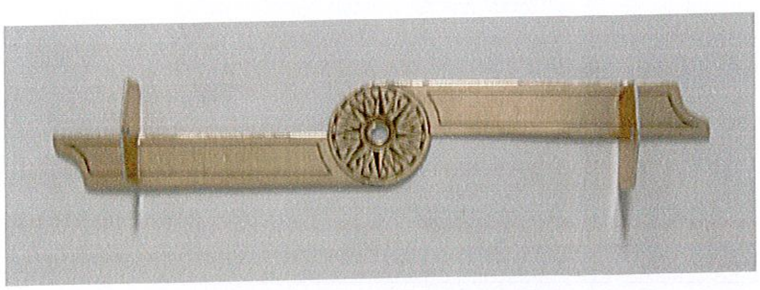
The tympan, climate, or plate is engraved with the coordinates of the celestial sphere. The zenith, horizon, and lines of altitude and azimuth are all drawn for a specific latitude. The circles of Capricorn and Cancer, the equator, and the meridian are also shown. These four circles are the same for all latitudes.

The Rule
The rule lies on top of the rete. It is used to line up the date on the ecliptic circle with the correct time on the hour circle.



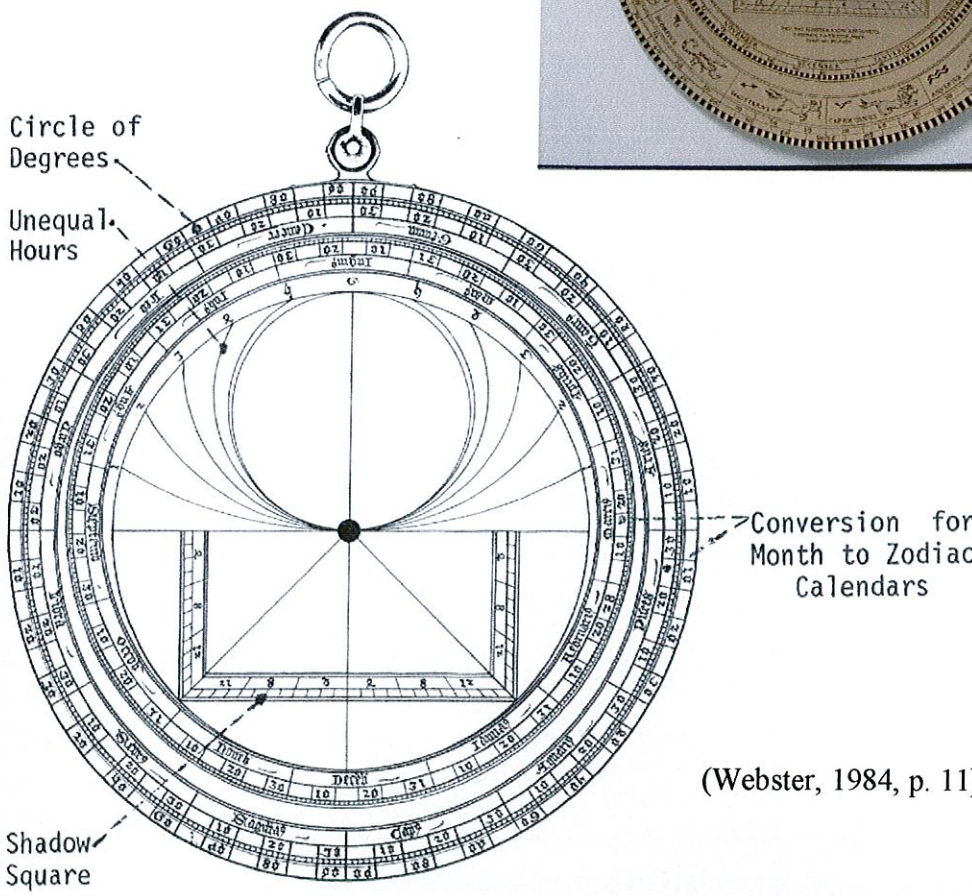
The Rete
The rete is basically the star map. The center hole marks the North Star. Other bright stars are indicated by named pointers. The path of the sun is shown by the ecliptic circle. This circle is divided into the twelve signs of the zodiac and forms a calendar on which the date settings are made.

The Alidade
The alidade is a sighting bar. It has pinhole sights and is used with the scales on the back of the astrolabe.



The Back of the Mother

Observations and measurements are made with the back of the astrolabe. There is a circle of degrees engraved around the edge and it is used to measure the altitude of the sun or a star.



(Webster, 1984, p. 11)

Glossary of Terms

Almucantar: A circle on the celestial sphere parallel to the horizon. Two stars with the same almucantar have the same altitude.

Altitude: The angular height of a body above the horizon. For example, a star has an altitude of 30° when the angle between the star, observer, and horizon is 30°.

Armillary sphere: In early astronomy, an instrument consisting of metal rings that represented the main circles of the celestial sphere. Another name is spherical astrolabe.

Astrolabe: In early astronomy, an instrument used to measure the altitude and positions of celestial bodies.

Astronomical Clock: A clock that measures sidereal (star) time, not solar time. It has special mechanisms and dials to display the relative positions of the sun, moon, zodiacal constellations, and sometimes major planets.

Astronomy: The science involving the observation and explanation of events occurring beyond Earth and its atmosphere. The word comes from the Greek and literally means "law of the stars."

Azimuth: The horizontal component of a direction, measured around the horizon from the North point toward the East (i.e. clockwise). The azimuth of a star is measured in degrees clockwise along the horizon from the North Pole to the foot of the star's vertical circle.

Catalogue of Stars: A list of stars giving details of apparent positions in space (right ascension and declination), their brightness (magnitude), and other information (ex. their spectral class, proper motion, etc.).

Celestial Equator: A great circle on the imaginary celestial sphere, which could be constructed by inflating the Earth's equator until it intersects with said sphere.

Celestial Latitude: The angular distance of a star, measured from the ecliptic along a great circle which is at right angles to the ecliptic.

Celestial Longitude: The angular distance of a heavenly body, measured along the ecliptic in an eastward direction, counted from the First Point of Aries.

Celestial Poles: On the celestial sphere, those points which correspond to the Earth's North and South poles. They can be pictured as extensions of the Earth's axis.

Celestial Sphere: The stars and planets appear to move along the inner surface of a great hollow globe, one hemisphere of which you see as you observe the stars. The Earth lies at the center of the celestial sphere.

Clock Stars: Stars used by astronomers to check the accuracy of clocks.

Declination: The angular distance of a star or planet north or south of the celestial equator, measured along a great circle passing through the star or planet and the celestial pole. A star north of the equator has a (+) declination; south it has a (-) declination.

Declination Circle: A great circle passing through the celestial pole. The declination of heavenly bodies is measured on the declination circle.

Ecliptic: The path the Sun appears to travel across the sky in one year. It forms a great circle on the celestial sphere.

Equator: An imaginary line drawn around a planet, halfway between the poles, where the surface of the roughly spherical planet is parallel to the axis of rotation.

First Point of Aries: Point where the sun crosses the celestial equator in spring, traveling in a northward direction (also called vernal equinox).

Great Circle: A circle on the surface of a sphere that has the same diameter as the sphere, dividing the sphere into two equal hemispheres.

Nadir: On the celestial sphere the point opposite the zenith.

Right Ascension: On the celestial sphere, the equivalent of terrestrial longitude. It is measured eastward along the celestial equator, beginning at the First Point of Aries.

Signs of the Zodiac: The 12 constellations which lie along the sun's path across the heavens.

Tropic of Cancer: The parallel of latitude that runs 23° 26' 22" north of the Equator, and the farthest northern latitude at which the sun can appear directly overhead.

Tropic of Capricorn: The parallel of latitude that runs 23° 26' 22" south of the Equator, and the farthest southern latitude at which the sun can appear directly overhead.

Zenith: The point on the celestial sphere directly above the observer's head.

Zenith Distance: The angular distance of a celestial object from the zenith of the observer.

Zodiac: The zone stretching around the sky along the ecliptic. More specifically, an imaginary belt in the heavens extending approximately 8 degrees on either side of the ecliptic.

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