

Chapter 2

The Naked Eye Era

In the centuries before crosswords and computer games, trying to understand the motions of the stars and planets across the sky provided the best intellectual challenge that a curious mind could face.

Some changes, such as the day-night cycle, are easy to describe and predict, while others, such as the retrograde motions of the planets, are not. Subtleties such as the changing speed of the Moon's motion require careful observation, while the changing length of the seasons is obvious to anyone who tries to grow food.

There are many excellent books concerned with the early history of astronomy. The main focus of most of these books is our ancestors' attempts to understand the motions of the Sun, the Moon, and the five naked-eye planets against the much steadier background of stars. The works of Claudius Ptolemy and of Nicolaus Copernicus, two of the greatest astronomers ever, are almost entirely concerned with visualizing and predicting the paths of these nearby objects.

In this book we can skip rapidly over much of these parts of our history, since our focus is on the discovery of new objects rather than the behavior of those that have been known since prehistoric times.

But let us not forget our debt to the Moon and planets: the quest to understand their motions encouraged logical thought, pushed mathematics to new limits and inspired Isaac Newton to invent what we now call physics. If the Moon and planets of our solar system had not existed, or if they had been too faint to be seen with the naked eye, or if the earth's skies had always been cloudy, the development of all the sciences and much of civilization would surely have been delayed by many centuries.

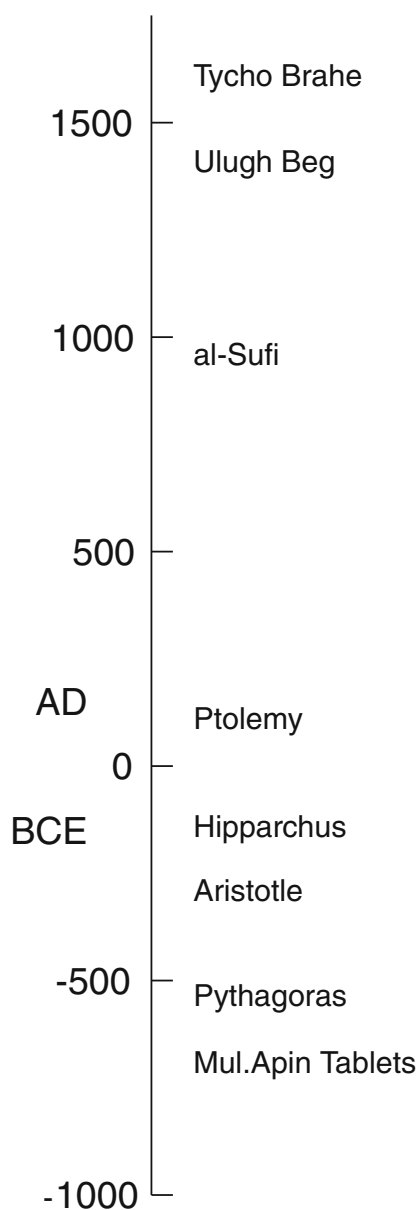


Fig. 2.1 Timeline for the naked eye era



Fig. 2.2 Mul.Apin clay tablet showing text on both sides

2.1 The Babylonians and the Mul.Apin Tablets

The oldest written star catalog we know of dates from the Babylonian era, about the 8th century BCE. It takes the form of small clay tablets crammed with cuneiform text (Figure 2.2). Several nearly identical groups of tablets have been found which describe the constellations that were identified by the Babylonians. They are referred to as the Mul.Apin tablets, after the first words of the texts.

Besides containing extensive descriptions of how the night sky changes over the months and seasons, the Mul.Apin tablets include a catalog of 71 constellations and stars, most of which have been identified with their modern counterparts (Figure 2.3). Some of these Babylonian constellations are direct precursors of those still in use today. For example we can easily recognize the descriptions of a scorpion (Scorpio), of twins (Gemini), and of a bull (Taurus). Most of the features listed in the Mul.Apin catalog are groups of stars, but there are a few individually identifiable stars, such as Arcturus and Sirius. The preference of the Babylonians for naming constellations rather than stars is perhaps a clue to understanding ancient attitudes to them. Nowadays we are used to thinking of a star as a hot ball of gas, perhaps with planets orbiting it. But to the Babylonians, and the Greeks that followed them, the stars had no more physical reality than the spots of light projected onto the dome of a planetarium. Their unchanging patterns—the constellations—were far more interesting to the ancients than were the stars themselves, both as markers for the motions of the planets and as inspirations for their cultural myths.

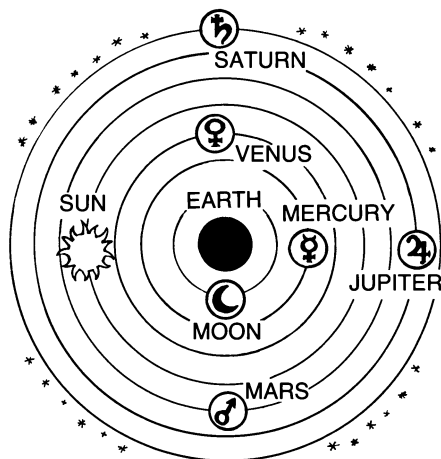


Fig. 2.4 The Aristotelian universe, with the Earth at its center and all the stars in a spherical shell around it

planets were the “immutable stars” in a spherical shell, all at the same distance from the Earth. This model, elaborated by Claudius Ptolemy several centuries later, survived for nearly two millennia until the time of Copernicus and the acceptance of the idea that the planets revolve around the Sun, not the Earth.

The earliest survey we know of that recorded actual numerical positions of stars was that of Timocharis (320–260 BCE) who listed the coordinates of 18 stars. We no longer have his data, but his measurements were used and discussed by several later astronomers. We know much more about the work of the great astronomer Hipparchus (190–120 BCE) who meticulously catalogued the positions of 850 stars. This number corresponds to most of the stars that can be seen with the naked eye from a European latitude.

Hipparchus developed and used some kind of armillary sphere (Figure 2.5) to make his measurements and achieved a positional accuracy of about half a degree—the diameter of the Earth’s moon. The accuracy of Hipparchus’ star positions allowed him to make several important discoveries. He came up with models for the motions of the Sun and the Moon and used these to predict eclipses. Most famously, by comparing his own measured positions for certain stars with those made by Timarchus 150 years earlier he discovered precession—the slow change in the direction of the Earth’s rotation axis (see Appendix A.5). He also invented trigonometry, measured the length of the year to within seven minutes, and invented the magnitude system for describing the brightness of stars (see Appendix A.6).

Unfortunately, we do not possess any original copies of Hipparchus’ star catalog, but there is good evidence that Ptolemy’s star catalog in the *Almagest*, published some 250 years later, relies heavily on Hipparchus’ data. The evidence for this assertion is based on the fact that the positions of the stars in Ptolemy’s catalog differ from what one would expect if he had made his own observations in the second

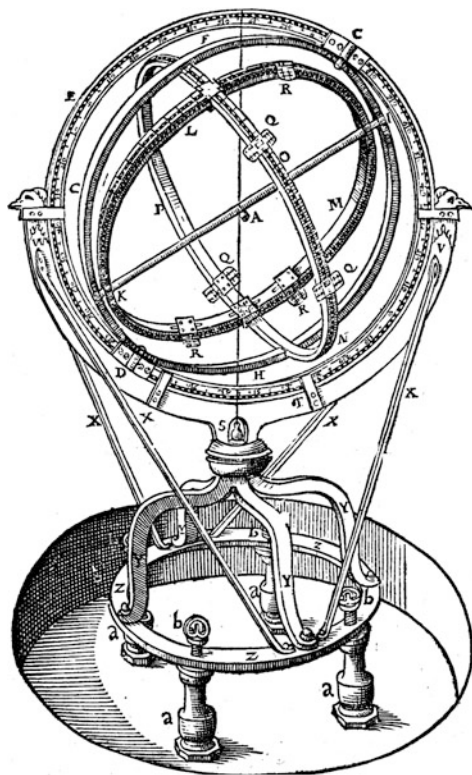


Fig. 2.5 This armillary sphere was built and used by Tycho Brahe, but is probably broadly similar to the one developed and used by Hipparchus. Measuring the position of a star with this device involves carefully aligning one of the brass rings along a North-South line through the zenith, and another to the ecliptic—the apparent path of the Sun through the sky. The star's position can then be read off the scales drawn on the appropriate rings

century AD. However, they are just what one would expect if Ptolemy had used Hipparchus's 250-year old data and precessed them using what we now know to be an incorrect formula. We can criticize this action of Ptolemy, and we can criticize his advocacy of the geocentric theory of the universe, but we should not lose sight of the fact that his major treatise, the *Almagest*, stands as one of the most important books ever written—the bedrock of astronomy and science for more than a thousand years.

Neither Hipparchus nor Ptolemy left us with a two-dimensional map of the sky, but Figure 2.6 shows a 2nd-century AD Roman copy of a Greek statue of the god Titan holding up the heavens on his shoulders. The surface of the globe contains illustrations of over 40 identifiable constellations as well as lines that correspond to the equator, the ecliptic, and the Arctic and Antarctic circles. This is the oldest known visual representation of the sky in existence, though there is controversy over whether the original dates from the time of Hipparchus or the time of Ptolemy.



Fig. 2.6 The statue of Titan holding a sky globe at the National Museum of Archaeology in Naples, Italy. It is sometimes referred to as the “Farnese Atlas.” Image credit:Wikimedia

2.3 Islamic Astronomy

Hipparchus's sky survey, as incorporated into the work of Ptolemy, ruled unchallenged for a thousand years, but improvements came with the rise of Islamic astronomy in the 10th century AD.

The Book of Fixed Stars (see Figure 2.7), written by the Persian astronomer Abd al-Rahman al-Sufi around 964 AD, was primarily an attempt to introduce Ptolemaic ideas to the Muslim world, but it broke new ground in two important ways. First, it gave every star a name, rather than just a location within a constellation. Many of these Arabic names are still in everyday use today, including Aldebaran, Betelgeuse, Deneb, Fomalhaut, Rigel, and Vega. Second, it contains the earliest recorded observations of what we now know to be external galaxies, namely the Andromeda galaxy, to which he gave the description “little cloud,” and the Large Magellanic Cloud. In making the latter discovery, al-Sufi had the advantage over Ptolemy of living at a lower geographic latitude, since the Magellanic Clouds are too far south to be visible from Greece.

Nearly 500 years later, Ulugh Beg, the governor of Samarkand, founded a Madrasah, or university, dedicated to the study of astronomy. He also set in motion the construction of what was probably the first observatory in the world to involve permanently constructed instruments, the largest of which was a giant 40-meter radius quadrant (see Figures 2.8 and 2.9). With this instrument Ulugh Beg and his colleagues produced a star catalog that had about the same number of stars as Ptolemy's but better accuracy and fewer errors. Those parts of the observatory which were built above ground were destroyed in 1449, but the section of the large sextant that had been built underground survived and was rediscovered in 1908. The observatory has since been reconstructed as a museum. Ulugh Beg was also a great mathematician, producing tables of sines and tangents that were accurate to eight decimal places, and measuring the length of a year to within half a minute.



Fig. 2.7 The Ursa Major constellation as mapped by al-Sufi. This image is taken from the oldest extant copy of his Book of the Fixed Stars, dated around 1009 AD



Fig. 2.8 Reconstructed buildings of Ulugh Beg's observatory in Samarkand, now part of Uzbekistan. This building houses the quadrant seen below. Light enters the quadrant through the doorway on the left of the picture. Image credit: Wikipedia

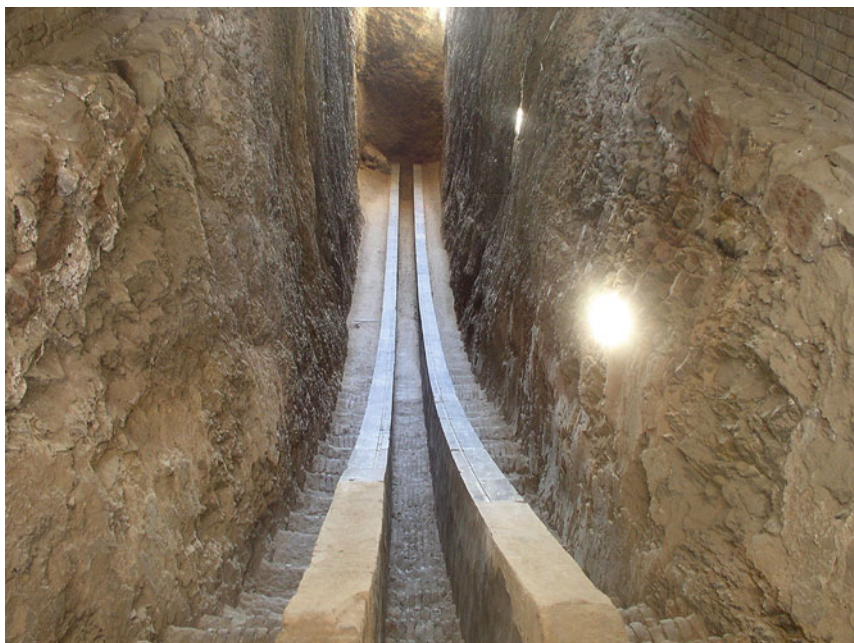


Fig. 2.9 The giant 40-meter radius quadrant that was used to measure the positions of stars and planets at Ulugh Beg observatory. Image credit: Alex Ostrovsky

2.4 Chinese Astronomy

Although ancient Chinese astronomers never attained the level of mathematical precision reached by Greek and Islamic astronomers, they paid great attention to mapping the positions of the stars in the sky. Figure 2.10 shows a small part of an extensive map of the sky discovered in 1907 in a cave in Dunhuang, on the Silk Road in western China. The map dates from somewhere between the 7th and 10th century AD, and is the oldest known paper-based map of the sky. It contains about 1,500 stars, considerably more than Ptolemy's *Almagest*.

Chinese astronomers also seem to have paid more attention to transitory phenomena than their western cousins, keeping extensive records of comets, novae, and even sunspots. In fact, the oldest astronomical records we know of are Chinese; they include oracle bones that refer to a solar eclipse that is known to have occurred in 1281 BCE, and to either a nova or a supernova that occurred about 1300 BCE.

Some of these records have turned out to be of great astrophysical significance, notably the report of a “guest star” in AD 1054, which many centuries later was identified as the supernova explosion that produced the Crab Nebula. Knowledge of the time since that explosion, plus the descriptions of how the brightness of the new star varied from day to day, have been of great value in understanding the physics of this remarkable object.

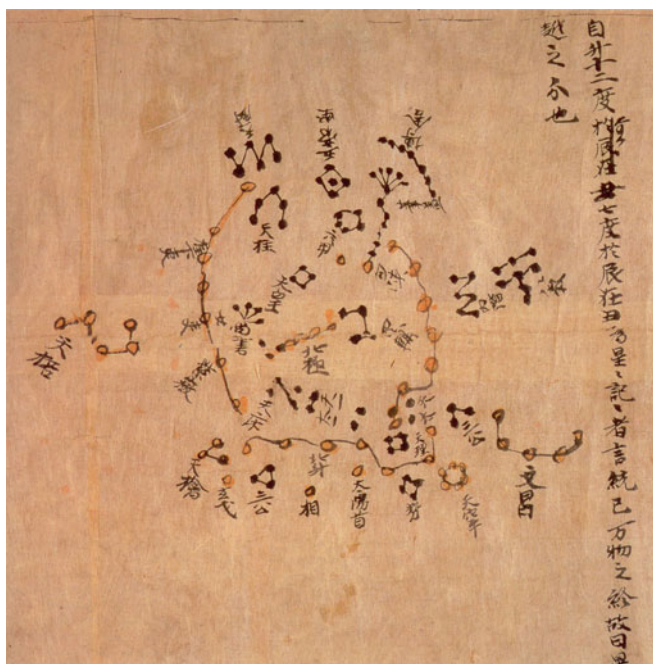


Fig. 2.10 Part of the Dunhuang star map showing the region around the north celestial pole

2.5 Tycho Brahe

Hipparchus's sky survey, as incorporated into the work of Ptolemy and Ulugh Beg, saw few major refinements until Tycho Brahe (1546–1601) decided to devote his career to astrometry—the precise measurement of star positions. Tycho was inspired by two celestial events early in his career; the appearance of bright new star in 1572, and of a comet in 1577.

Aristotle's view that the stars and the constellations were forever unchanging still held sway in Tycho's time; anything that moved or fluctuated in brightness was assumed to be occurring within the Earth's atmosphere. The new star of 1572, for which Tycho coined the word *nova* but which we would now classify as a supernova, gave him a chance to test this assumption. He realized that if the new star was closer than the Moon, as widely believed, he should see parallax as the Earth's daily rotation carried him from east to west. And if it belonged to the realm of the planets he should also see proper motions from day to day as the object moved in its orbit. The fact that he could detect neither kind of motion during the whole year that he could observe it indicated to him that the supernova belonged to the realm of the distant stars; it therefore violated Aristotle's premise that the stars were immutable. Several years later he applied the same test to the bright comet that lit up the skies in 1577; he showed that it was moving at a rate consistent with it being in a planet-like orbit—far above the Earth's atmosphere where comets were then supposed to exist—but much closer than the fixed stars.

Emboldened by this demonstration of the scientific value of precise astrometry, he sought and found a rich sponsor to finance his research activities. At Hven, in what was then Denmark but is now Sweden, he built the Uraniborg Observatory—a spacious building for himself and his staff that incorporated a number of specially designed angle-measuring instruments (Figure 2.11). All of the instruments required human observations with the naked eye: Tycho died several years before the telescope was invented.

One of the ways in which he and his assistants made their observations is shown in Figure 2.11. The large, precisely-engraved quadrant in the foreground was aligned exactly in a north-south direction and was used to measure the angle of a star above the horizon when it transited the meridian, as well as the precise time at which it did so. To achieve this, the bearded man at the far right of the picture faces the wall to the south of the quadrant which contains a small window with a pair of crossed wires in it, one vertical and one horizontal. As the star approaches the center of the window he adjusts the position of a sliding marker on the quadrant so that the star lines up with the horizontal wire in the window. He then watches the star move horizontally across the window and shouts when it crosses the vertical line. The man at the bottom right then reads out the time on the clock and the scribe at the lower left writes down both the time and the angle of the quadrant. From these two numbers the coordinates of the star can be calculated.



Fig. 2.11 Tycho Brahe at his Uraniborg observatory showing several of the instruments he used, including the large quadrant and the clock in the foreground

The first draft of Tycho's star catalog, circulated in 1598, contained 1004 stars with a positional accuracy of about half a minute of arc—sixty times better than Hipparchus. It was the first catalog to include corrections for atmospheric refraction—the bending of light as it passes through layers of different density.

At the same time as he was compiling his star catalog, Tycho and his staff carefully recorded the ever-changing positions of the Moon and planets against the

background of the fixed stars. It is for these observations that we owe our greatest debt to him; his one-time assistant Johannes Kepler pored over these data for many years trying to find the patterns that governed the orbits of the planets. In 1609 he published his discovery that the planets move in elliptical orbits around the Sun contradicting once and for all the Ptolemaic insistence that all celestial motions were based on circles. Kepler did not try to provide any physical explanation for his laws of planetary motion, but eighty years later Isaac Newton proved that they are a mathematical consequence of his three laws of Motion plus his Universal Law of Gravity. If Tycho Brahe had not measured the positions of the planets as accurately as he did, Kepler would not have been able to show that Ptolemy's circle-based theory did not fit the observations satisfactorily. We must therefore thank Tycho Brahe and his meticulous astrometry for providing the secure foundation for what we now refer to as Classical Physics.

A few years later, in 1603, the German astronomer Johann Bayer used Tycho's catalog to create a star atlas called *Uranometria* (Figure 2.12). This atlas broke ground in two ways. First, it covered the whole sky, making use of the southern hemisphere observations of about 300 stars by the Dutch navigator Frederick de Houtman. Second, it introduced the constellation-based star naming system that is still in use today. In this system, stars within a constellation are named with Greek letters in order of decreasing brightness. Thus Betelgeuse, the brightest star in the Orion constellation is named α Orionis while the second brightest star, Rigel, is named β Orionis.



Fig. 2.12 The Orion region from Johann Bayer's *Uranometria*, showing the first use of Greek letters to describe the relative brightness of the stars in a constellation

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