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HISTORY OF THE OBSERVATORY AS AN INSTITUTION: FROM MARAGHA TO MOUNT WILSON

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ABSTRACT

The astronomical observatory has existed since ancient times and has served a number of public causes—religious, astrological, practical, and, more recently, scientific. In this thesis, I show how the observatory underwent three major transitions, beginning with its "institutionalization" in the thirteenth century, with the founding of the Maragha Observatory. I discuss how the Maragha observatory (located in the northwestern part of Persia) became a model for future observatories, including the Mount Wilson Observatory. The Maragha Observatory produced a revolutionary school of thought known as the "Maragha School." This school marked a sharp departure from Ptolemaic Greek astronomy. I argue that Copernicus should be seen as belonging to this school as its last and most known follower. The observatory went through a second transition with the introduction of the telescope. The telescope opened new channels of inquiry. Galileo's observations of our moon's surface, sunspots, the moons of Jupiter, and the phases of Venus, started a race to improve the telescope in order to obtain ever higher resolution images. The third transition occurred when astronomers became concerned with questions having little or no practical use. This era, which began in the nineteenth century and extends into our own time, was defined by the quest for pure knowledge. It occurred as a result of major improvements in instrumentation and with development of spectroscopy, which gave birth to the field of astrophysics.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

This thesis will chart how the observatory changed over time, from the thirteenth century through the twentieth century, from Maragha to Mount Wilson, from Persia to Pasadena, and from Arabs to Americans. First, some background.

The astronomical observatory is an old institution. It began in many forms that reflected an attempt to study the observed objects in the heavens. The observatory gradually went through a transition into an observational post, and eventually matured into a permanent facility with the sole purpose of observing the sky. For the longest time, such astronomical observational centers were associated with astrology, often of interest to local rulers. Gradually, observatories divorced themselves from astrology to emerge finally as pure scientific research centers.

For our purposes, an institution refers to a long-established practice that is devoted for a particular public cause. The most ancient form of science, which has maintained continuity throughout recorded human history, is observing the sky. Before the Medieval era, the ancient Babylonians, Egyptians, African and South American tribes, north western European cultures, ancient Chinese, Indians, and Greeks all observed the heavens. The common thread among all civilizations is a keen interest in the motion of heavenly objects. Such interest in the heavens was often religious in purpose; farming was also important given the need to predict the seasons for planting and harvesting.

The earliest written astronomical records date back to the Ancient Egyptians and the Babylonians in the third, second, and first millennia BC. The Egyptians, who worshiped the sun god Ra, followed a solar calendar. This solar calendar year was divided into twelve months, and each month into thirty days making the year equal to 360 days in length, plus an additional special five-day unit. Each day was further divided into twelve daytime segments and twelve nighttime segments. Hence our solar calendar today has its roots in the Egyptian calendar and our hour is also of Egyptian origin.[1]

Babylonian astronomy was very sophisticated; the Babylonians recorded a catalogue of stars and constellations. They developed tables that predicted the lunar year changes over a period of 210 years. They used the sexagesimal number system that was based on the number sixty; hence the subdivision of an hour and an angle into sixty minutes and each minute into sixty seconds is Babylonian in origin.

Much of Greek astronomy has its roots in Babylonian astronomy. It is worth mentioning that the Greek astronomer, Ptolemy (150 AD), made use of Babylonian observations from the first millennium BC, including eclipse records; so did Hipparchus (mid-second century BC) before him.[2] The ancient Greeks, namely Eudoxus of Cnidus (fourth century BC) who was a disciple of Plato, proposed the first mathematical model that accounts for the motions of heavenly objects. Eudoxus explained that "the complex apparent paths of the sun, moon and planets were, in each case, produced by the simple circular movements of a certain number of concentric spheres. The earth is at rest at the

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[1] Asger Aaboe, *Episodes from the Early History of Mathematics* (Mathematical Association of America, Washingotn, D. C., 1964), p. 22.

[2] John Britton and Christopher Walker, "Astronomy and Astrology in Mesopotamia," in *Astronomy before the Telescope*, ed. Christopher Walker, (St. Martin's Press, 1996), p. 50.

common centre of all the spheres, but their axes are inclined to one another and they rotate at different, though uniform speeds."[3]

Arabic astronomy has its roots in Greek astronomy.[4] In the Islamic world, astronomy was arguably the most important field in which Arabic science was at the forefront of development during the Middle Ages. This was due to practical reasons such as determining the different times of the Islamic prayers that depended on the positions of the sun throughout the day. It was also important to determine the correct direction of Mecca to which Muslims faced when performing prayers; hence the determination of geographical longitude was necessary for such a purpose, which, in turn, depended on observations of the stars. However, the advances that took place within Arabic astronomy did not occur in a scientific vacuum; on the contrary, medicine for example, became one of the most important fields developed by Arabic scholars. In addition to the two abovementioned disciplines, Arabic scientists made significant developments in every field of science known at the time, including mathematics, optics, chemistry, pharmacy, and engineering.

One of the most important developments in astronomy was the observatory. Throughout the Islamic world many observatories were built. Early ninth century observational posts were short-lived (2-3 years life span) and had limited programs of

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[3] G.E.R. Lloyd, *Early Greek Science: Thales to Aristotle*, (W. W. Norton & Company, New York, 1970), pp. 86-87.

[4] Arabic astronomy refers to astronomy written in Arabic during the period spanning the eighth through the fifteenth centuries. Arabs and non-Arabs (e.g. Persians) living in territories ruled by Muslims, all made contributions in astronomy and other sciences. Those who made scientific contributions included Muslims, Christians, and Jews. Arabic was the language of science during that time period of the Islamic civilization; this is why we use the word "Arabic" to define what was recorded in Arabic. For the same reason we will refer to those who wrote science in the Arabic language as Arabic scholars or scientists, with the understanding that many were non-Arabs who had a different mother tongue they spoke at home. One of the things I am able to do in this thesis is to draw on some original Arabic sources. Although I am using sources in their original Arabic, I will translate them myself.

observation (mainly observing the sun and moon). In the tenth and eleventh centuries they eventually matured into observatories. The culmination of the observatory experience as a scientific institution came in the thirteenth century with the founding of the Maragha Observatory. This particular observatory holds a special place in the history of observatory development; Maragha was a center for scientific research that housed astronomers who revolutionized mathematical astronomy and provided breakthroughs in natural philosophy. Hence, these astronomers created what George Saliba refers to as the "Maragha Revolution."[5] In addition, the Maragha Observatory played a major role as a "transmission belt" not only of ideas that re-shaped mathematical astronomy in Europe, but also in influencing future observatories, especially those in Samarqand and Istanbul, which in turn influenced future European observatories.

The Maragha Observatory was founded in Maragha (in the current day East Azerbaijan province in northwestern Iran) in the thirteenth century; Nasir al-Din al-Tusi was director.[6] In a relatively short time span, the Maragha Observatory became an important international center for research and learning in central Asia. Al-Tusi was initially captured by the Mongol commander, Hulegu, in northern Persia (southeast of Maragha). He was forced to move to Maragha. Hulegu believed in the astrological advice given by astronomers, especially by al-Tusi whose fame reached as far east as China. Hulegu assigned the position of chief astronomer to al-Tusi who began to set plans for building the observatory at Maragha in order to make new and more accurate

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[5] George Saliba, *A History of Arabic Astronomy: Planetary Theories during the Golden Age of Islam,* (New York: New York University Press, 1994), pp. 245-257, esp. p. 250.

[6] Nasir al-Din al-Tusi, the famous Persian astronomer of the thirteenth century who was employed by the Isma'ilis (known as the Assassins), in north western Persia. When the Isma'ili fortress, Alamut, fell to Hulegu, he preserved the life of al-Tusi and his library of scientific books to bring with him to Maragha.

observations. Al-Tusi was a central figure within the astronomical tradition that developed at Maragha and thereafter. He invented a mathematical theorem, known as Tusi's Couple, which corrected certain astronomical problems and revolutionized a key component of Aristotelian natural philosophy.[7] As the head astronomer of the Maragha Observatory project, he contacted and recruited astronomers from distant lands to help build and staff the observatory. Mu'ayyad al-Din al-Urdi came from Syria, Fao-Mun-Ji came from China, Muhyi'l-Din al-Maghribi came from Andalusia (Islamic Spain) and Qutb al-Din al-Shirazi came from Shiraz, Iran. It is in this regard that George Sarton refers to the "internationalism" of the Margha Observatory.[8]

Al-Tusi (among other Maragha scientists) made significant and lasting alterations in the Ptolemaic astronomical models that were later echoed by future astronomers as well as Copernicus. Among those who followed in the footsteps of the Maragha astronomers in the fourteenth through the sixteenth centuries were: Ibn al-Shatir from Syria, Ala' al-Din al-Qushji from Samarqand, Uzbekistan, and Shams al-Din al-Khafri (who was the last major Muslim astronomer of Maragha). In focusing on mathematical astronomy, Copernicus followed in the footsteps of his Muslim predecessors and was concerned with the same problems they were; for this reason Copernicus may well be considered the last of the Maragha School astronomers.[9] Even though the Maragha Observatory fell into ruin some time in the first quarter of the fourteenth century, the

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[7] See Figure 1, page 75..

[8] George Sarton, *Introduction to the History of Science*, Vol. 2, (Baltimore, MD: John Hopkins University Press, 1931), pp. 1005-1006.

[9] The term was first used by Victor Roberts, "The Planetary Theory of Ibn al-Shatir: Latitudes of the Planets," *Isis*, 57, No. 2 (1966), pp. 208-219, esp. p. 210. Subsequently, the term was codified by E. S. Kennedy, "Late Medieval Planetary Theory," *Isis*, 57, No. 3 (1966), pp. 365-378, esp. p.365.

momentum of ideas developed at Maragha played a central role in the development of astronomy.

The Maragha Observatory is historically significant because it was the first modern observatory. Maragha marked the first transition in the development of the observatory with respect to six points. First, Maragha attracted scientists from different corners of the world, bringing into focus the best minds and practices in astronomy that were known in the world at the time. This established the tradition of an international observatory. Second, the large-scale observational instruments that were built enabled more accurate observations to be collected in a new and improved *zij* (astronomical tables).[10] From then on, all observatories would use bigger (and fixed) observational instruments, with competing accuracy. Third, Maragha established the tradition of an observatory directorship. Fourth, the long-term observational program at Maragha became a model for future observatories east and west. Fifth, the Maragha Observatory set an example for the necessity of long-term funding, with public or private sources. Sixth, the Maragha scientists produced new theorems that were used in mathematical astronomy, and solved some of the problems present in Ptolemaic astronomy. In short, the observatory became a center for research in astronomy. The Maragha Observatory played a significant role in the vertical transmission of the best ideas in astronomy to future followers of the school as well as the horizontal transmission of those models and theorems across geographical regions. This development eventually changed the face of astronomy. These six abovementioned points became a standard that was incorporated into every future observatory.

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[10] This is the famous star catalogue known as *Zij-i Ilkhani* that was later revised in Samarqand by Ulugh Bey.

Later observatories used the Maragha Observatory as a model. Two important examples are the observatory built by Ulugh Bey in Samarqand, Uzbekistan, in the fifteenth century, and the Istanbul Observatory, which was founded in the sixteenth century by the Ottomans.[11] These two other Islamic observatories, especially the Samarqand Observatory, contributed significantly to the development of the early modern European observatories, such as the Kassel Observatory as well as those built by Tycho Brahe.

In turn, the early European observatories influenced later ones, including the Paris, Leiden, Copenhagen and, the most famous of all, the Royal Observatory in Greenwich, England. When the United States became an independent nation, U.S. observatories sprang up in many cities, such as the Hopkins and Harvard College observatories; naturally, they were modeled after the European observatory. It was during this time period that the telescope was incorporated into the observatory. The introduction of the telescope marked the second transition in the historic development of the observatory. Namely, the telescope allowed astronomers to begin to study the heavenly objects themselves and their characteristics. This is in contrast to recording only the positions of the heavenly objects in the past, until the telescope became an astronomical utility. The study of physical features of heavenly objects would propel astronomy in a direction away from positional astronomy, which had served practical purposes.

The industrial revolution played a key role in the rapid development of the telescope. With more powerful telescopes, higher resolution of stars and nebulae was

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[11] For famous observatories in Islam, see Figure 2, page 76.

available to astronomers. In the second half of the nineteenth century, a brilliant idea was married to the telescope. Sir William Huggins applied spectral analysis techniques used in the physics lab to analyze stellar light. What he discovered was that the sun was made of elements similar to those on earth. This gave birth to a new science called astrophysics (physics applied to astronomy), which marked a third transition in the observatory's development. The observatory became a permanent center for pure scientific research.

The Lick observatory in the United States emerged toward the end of the nineteenth century and inspired the founding of the Mount Wilson Observatory in the early twentieth century. It was during his thirty-four years at Mount Wilson’s observatory that Edwin Hubble made his famous discovery of an expanding universe. Such an expansion, when traced in the opposite direction of time, revealed a universe that was ever shrinking down to a single point. From that point of dense matter, the universe expanded rapidly in what is known as the big bang.

In this study I will illustrate the three major transitions of the observatory. I will trace the development of the observatory from its mature form at the Maragha Observatory to its modern form as represented by the Mount Wilson Observatory, where the birthplace of time was revealed. First, I will demonstrate how the observatory derived its foundational form and function, going back to the Maragha Observatory. Second, I will show the gradual shift that occurred with the advent of the telescope. Observatories gradually shifted away from recording the positions of the sun, moon, and planets, which aided navigation and had other practical uses. New astronomical observational interests were becoming more centered on the physical characteristics of the heavenly objects. The telescope, which made such physical observations possible, marked the second transition in the progress of the observatory. With rapid improvements in technology, higher-resolution telescopes, paired with cameras that could be mounted on them, suggested the idea of applying some of our laboratory physics experiments onto the stars. With the birth of astrophysics, the third transition was firmly established as the observatory would forever become a center for pure research.

II. EARLY HISTORY OF OBSERVATIONAL ASTRONOMY

1. Astronomy in Antiquity

The ancient Egyptians bequeathed to us two systems that emerged from their astronomical observations: the civil calendar of 365 days, and the division of the day and night into twelve hours each (today we divide an entire day into equal twenty-four hours rather than divide the night into equal twelve hours, and the day into equal twelve hours.) The origins of these two systems were religious, even though the first one evolved into its final form in order to regulate Egyptian's secular life. The ancient Egyptians worshiped the sun god Ra. They observed that the sun's location along the horizon gradually drifting day after day. The sun reaches its southernmost and northernmost turning points, along the horizon, twice a year marked as the summer solstice and winter solstice. Egyptian astronomy and religion are based upon this simple movement of the sun along the horizon. The early Egyptians determined the 365 year by simply counting the number of days it took Ra "to return each year to his birthplace on the south-eastern horizon at the winter solstice."[12] Ronald Wells informs us that they probably used "wooden stakes, cords and shadows" and that this method approximately "dated to sometime around 4500 BC."[13]

By contrast, the Babylonian calendar was based on both the moon and the sun. The first of the month began on the evening of the first visible crescent moon. The lunar calendar was kept in line with the solar year by inserting an extra lunar month at different intervals. It was always the king's decision to insert a month for the sake of reconciling the lunar and solar years. Here is a letter by the king Hammurabi of Babylon (1848-1806 BC) addressing such an intercalation.

> Tell Sin-iddinam, Hammurabi sends you the following message, 'This year has an additional month. The coming month should be designated as the second month Ululu, and wherever the annual tax had been ordered to be brought in to Babylon on the 24th of the month Tashritu it should now be brought to Babylon on the 24th of the second month Ululu.'[14]

This lunar calendar eventually evolved to a twelve-month calendar consisting of thirty days each, thus a year comprised 360 days. One of the descendants of this calendar is the zodiac system from which we derive our division of a circle's circumference into 360˚. By the beginning of the fifth century BC, intercalations followed a predetermined cycle; there were 7 intercalations within 19 years. The invention of such an intercalation cycle is often attributed to the Greek, Meton of Athens, who lived in the late fifth century, hence the name *Metonic Cycle*.

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[12] Ronald A. Wells, "Astronomy in Egypt," in *Astronomy before the Telescope*, ed. Christopher Walker, St. Martin's Press, 1996, pp. 33-34.
[13] Ibid., p. 34.
[14] John Britton and Christopher Walker, "Astronomy and Astrology in Mesopotamia," in *Astronomy before the Telescope*, ed. Christopher Walker, St. Martin's Press, 1996, p. 46.

Babylonian astronomy developed mathematically very rapidly. The Babylonians devised arithmetical techniques they incorporated into their lunar and planetary theories. By the fifth century BC the first day of the lunar month was predicted by computation rather than by observation. This fundamental discovery by the Babylonians was far reaching, "that it was possible to create mathematical models which would yield reliable numerical predictions of complex astronomical phenomena."[15] The idea that an astronomer could predict the future motion of heavenly objects motivated all subsequent astronomy.

The Babylonians also devised a mathematical almanac showing the positions of heavenly objects; this was one of their "principal contribution[s] to the science of astronomy."[16] They used the Babylonian sexagesimal cuneiform number system which is a place-value notation similar to the decimal system, but with base 60 instead of 10. For example, the number 1,1,1;1,1 = $1 \times 60^2 + 1 \times 60^1 + 1 \times 60^0 + 1 \times 60^{-1} + 1 \times 60^{-2}$.[17] (The punctuation is a modern addition for the purpose of illustration). The latest almanac was for the year 75 AD.

The contribution of the Babylonians to Greek astronomy is enormous. This is reflected in Ptolemy's catalogue of heavenly objects known as *Almagest*. Some of the Babylonian contribution included "many constellation names, the zodiacal reference system, the degree as the base unit of angular measure… [and] the use of sexagesimal fractions."[18] Another very important contribution was a catalogue of observations that

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[15] Ibid., p. 67.
[16] Ibid., p. 51.
[17] Ibid., p. 51.
[18] Ibid., p. 66.

date back to the beginning of the reign of Nabonassar in 747 BC without which Ptolemy would not have been able to devise his mathematical models of heavenly motions.

2. Greek Astronomy

There are two main Greek authorities in astronomy: Aristotle and Ptolemy. In Aristotle's view, the Earth "had to be motionless at the center of the universe in the same way every moving sphere must have a motionless point at its very center."[19] According to the cosmological model of Aristotle, the world was made up of real concentric spheres, with Earth at the center. To those spheres were attached the sun, the moon, the planets Mercury, Venus, Mars, Jupiter and Saturn, as well as the stars. As the spheres rotated, they carried along with them the celestial objects and created their motions. Thus Earth represented the point about which celestial objects rotated, and according to Aristotle, they did so uniformly (at constant velocity). Earth was also the point toward which terrestrial objects fell with rectilinear (straight-line) motion.[20] The legacy of Greek astronomy culminated in Ptolemy who lived in Alexandria, Egypt, in the second century AD. His most influential astronomical treatise is known as *Almagest*. Ptolemy concurred with Aristotle in placing the Earth in the center; this later became known as the Ptolemaic geocentric model of the heavens.[21] In his *Almagest*, Ptolemy proposed complex mathematical models to explain the apparent motions of the sun, moon, and the five known planets. One of the many issues in Ptolemy's models was his construction of

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[19] George Saliba, *Islamic Science and the Making of the European Renaissance*, (Cambridge, MA: MIT Press, 2007), 71-129.

[20] Aristotle's cosmological theory would not be replaced until the seventeenth century when Isaac Newton published a new cosmology theory based on the law of gravitation.

[21] Saliba, "Greek Astronomy and the Medieval Arabic Tradition," *American Scientist* 90, no. 4 (2002), pp. 360-367, esp. p. 362.

spheres, carrying the moon and the planets, rotating uniformly about a point off-center. The motion of such spheres is physically impossible according to Aristotelian physics. In order to understand this problem, try to imagine balancing a rotating basketball on a point that is off the center of the ball. This off-center point became known as the equant, and thus was the equant problem in Ptolemy's models which occupied future astronomers for over a millennium.

3. Early Islamic Observational Posts and Observatories

Islamic astronomy is still widely underreported in astronomy textbooks and educational media. As recently as 2007, on the History Channel, the popular educational program *The Universe*, Season 1, Episode 14, illustrates this point. The presenter, Erik Thompson, introduced the mathematical work of Ptolemy and explained how his system could help predict (even though inaccurately) the future of the motions and positions of the known planets. One of the astrophysicists featured on this program was Owen Gingerich who was from the Harvard Smithsonian Center for Astrophysics. Following the presentation on Ptolemy, Gingerich stated that "interestingly, astronomy seemed to stand still for centuries after that [Ptolemy]."[22] Thompson immediately elaborated on Gingerich's comment by saying "in fact, after the collapse of Rome in 476 A.D. astronomy *actually lost ground* [italics mine]."[23] Thompson, then, jumped from the fifth century to the fifteenth century to introduce Copernicus by saying "a thousand years later, a new theory would confront accepted beliefs about how the heavens worked and would

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[22] The History Channel, *The Universe: Explore the Edges of the Unknown (DVD)*, Season 1, Episode14 Beyond the Big Bang, 2007, min. 19:10-17.

[23] Ibid, min. 19:18-26.

move mankind closer to a theory of the Big Bang."[24] This history which dismisses the thousand years between Ptolemy and Copernicus is all too familiar in astronomy texts and media. The era often referred to as the Golden Age of Islam would witness remarkable advancements in mathematical astronomy that would, in fact, make possible the beginning of the Rennaisance.

The ancient Greek influence could be easily traced in the work of early Arabic astronomers. The equant problem was among many others that Arabic astronomers encountered when they began to translate the entire corpus of Greek science, including astronomy, into Arabic. What has become known as Arabic science was initiated in the eighth century, reaching its height in the ninth century in Baghdad, under the Abbasid caliph al-Ma'mun, at the intellectual center known as Beit al-Hikmah, or House of Wisdom. Muslim, Christian and Jewish scholars took part in this massive translation endeavor; however, they went beyond just mimicking the Greek texts. In this paper I will refer to the scholars who contributed to Arabic science as Arabic scholars since they wrote their work in Arabic, even though their mother-tongue at home may have been different.

In astronomy Arabic scholars translated all the work of Ptolemy; his most famous book, *Almagest*, became known by its Arabic name. George Saliba informs us that by the second half of the ninth century, "we witness the creation of the discipline of *Hay'a*, as in *ilm al-hay'a*, which did not have a Greek parallel".[25] *Ilm al-hay'a* focused purely on mathematical astronomy and was totally dissociated from astrology. By the time the

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[24] Ibid, min. 19:34-49.

[25] Saliba, *Islamic Science,* p. 18.

Maragha Observatory was built, problems in the Greek astronomical texts were well defined and addressed in many books. One such important example that influenced later developments in Arabic astronomy is work by the eleventh century scholar, Ibn al-Haytham; he was the first Arabic astronomer to bring attention to the problematic Ptolemaic constructions. He wrote a commentary entitled *al-Shukuk* (Doubts about Ptolemy) in which he detailed problems in Ptolemy's representations. Ibn al-Haytham stated that Ptolemy's conflicting analysis was "in his assumption of the movements [of the planets as physical objects] along *imaginary* [italics mine] circles rather than physical ones."[26] Ibn al-Haytham simply challenged the physical impossibility of the equant. The issues with Ptolemy's work were later tackled by many Arabic astronomers, especially those at the Maragha Observatory.

New and more accurate observations were needed in order to make corrections to the Greek texts. To serve that purpose, the caliph al-Ma'mun founded two observatories, one in Baghdad and the other in Damascus (the latter served more as an observational post). Saliba informs us that early in the ninth century new measurements for the inclination of the ecliptic (this is the same as the angle of earth's axial tilt) were made, and Ptolemy's value for the inclination of the ecliptic was found to be too large.[27] The measurements that took place in Baghdad gave us a value that we still use today.[28] Another example of the many corrections made to the Ptolemaic astronomical parameters was that of the motion of precession. (Our earth's axis rotates in the same manner the

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[26] Ibn al-Haytham, *al-Shukuk (Doubts about Ptolemy)*, (Cairo, Dar al-Kutub, Egypt, 1971), pp. 5-70, esp. p. 38. The Arabic text I translated above is the following:
"لأن التناقض الذي لزمه في هيئات حركات الكواكب إنما لزمه من أجل فرضه الحركات في دوائر و خطوط متخيلة ، لا في أجسام موجودة، فلما فرضت في أجسام موجودة لزم منها التناقض."

[27] Ptolemy's inclination of the ecliptic was 23:51,20° which was too large. This is compared to the value al-Ma'mun's astronomer determined from new measurement which was 23;33 °, a value we still use today.

[28] Saliba, *Islamic Science*, p. 81.

axis of a top rotates when the top is spun).[29] Ptolemy had recorded in his *Almagest* that the motion of precession was 1 degree every 100 years. Arabic astronomers found in the early ninth century that the motion of precession was 1 degree in 66 years which is much closer to the modern value of about 1 degree every 70 years.

In addition to state-sponsored astronomical observations and calculations, other scholars such as al-Battani, an astronomer from Harran who had a private observatory in Raqqa, developed his own astronomical tables based on his own observations over the span of 40 years (887-918). His astronomical observations would later be quoted by many astronomers, including Copernicus.

III. TRANSITION ONE: MARAGHA OBSERVATORY: EARLIEST MODEL OF THE MODERN OBSERVATORY

1. Maragha Observatory: Birth of a Modern Observatory

Maragha is located in northwestern Iran about eighty kilometers south of Tabriz. When Hulegu commanded his Mongol army through Persia in the thirteenth century, he seized the Isma'ili fortress, Alamut, located about 400 km southeast of Maragha. Alamut was the place where Nasir al-Din al-Tusi (1201-74) had been living and producing texts in astronomy for many years. Al-Tusi's fame as astronomer had reached the Mongols in the east who had an intense interest in astronomy for astrological reasons. Therefore, when Hulegu captured the Alamut Fortress in 1256, he preserved the life of al-Tusi along

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[29] Earth's axis rotates once in almost 26,000 years, causing the seasons to gradually change. For example, about 13,000 years from now when earth's axis is tilted in a direction 180 degrees from the direction it is currently pointing in, July would be in the middle of winter for the northern hemisphere

with his library of scientific books. In it worth mentioning that the Mongol Khan at the time, Mongke Khan, had intended on building an observatory is his capital Karakurum. He had commissioned his brother, Hulegu, to bring back al-Tusi to build such an observatory, but died in 1257 before he could realize his plans.

Founding the Maragha Observatory owed much to the Mongols. Hulegu ordered its construction in 1259, as was mentioned by al-Tusi at the beginning of the *Zij-i Ilkhani* (Ilkhani astronomical tables).[30]

Even though Rashiduddin boosted Hulegu's image as one who has great concern for science, the latter's fondness of science seemed to focus more on "pseudo-sciences such as astrology and alchemy."[31] Rashiduddin alludes to this fact regarding Hulegu in the following passage.

> He was exceptionally fond of the science of alchemy, and its practitioners received extraordinary patronage from him. According to their own delusions and fancies they lit fires, burned innumerable potions, and spouted a lot of useless hot air to young and old alike about making "pots of the clay of wisdom," but the benefit of it reached nothing but their nostrils and palates. In transmutation they had no luck, but they were miracles of cheating and fraud, squandering and wasting the stores of the workshops of lordly power. In supplying them, meeting their demands, and paying their salaries, more was spent than Qarun[32] made by alchemy in his whole life.[33]

Nonetheless, Hulegu's interest in retaining Nasir al-Din al-Tusi in his Ilkhanid state, and his keen intent on seeing the Maragha Observatory to completion in his lifetime is only indicative of a genuine interest in astronomy despite his preoccupation with astrology

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[30] Aydin Sayili, *The Observatory in Islam*, (Ankara: Türk Tarih Kurumu Basımevi, 1960), p.191.
[31] Aydin Sayili, *The Observatory in Islam*, p. 193.
[32] Qarun is the Islamic equivalent of Croesus, a biblical figure whose touch turned everything to gold.
[33] Rashiduddin, *Jami u t-tawarikh (Compendium of Chronicles)*. English translation by W.M. Thackston. (Harvard: Harvard University Department of Near Eastern Languages and Civilizations, 1999), p. 513.

,which seems to be the driving motive and the “main purpose for the foundation for the Maragha Observatory.”[34] It is this interest that provided the circumstances to build the Maragha Observatory that helped propel the science of astronomy forward.

Nasir al-Din al-Tusi would become one of the most trusted advisors to Hulegu, mainly because of his knowledge of the motions of heavenly bodies and his ability to predict their future positions. To Hulegu, this meant al-Tusi could provide deep astrological insights into future events that influenced his Ilkhanid state. It is believed that Hulegu consulted the famous al-Tusi at the seize Baghdad in 1258. The city of Baghdad was eventually sacked by the army of Hulegu, and the rumor of al-Tusi's advice to Hulegu would affect al-Tusi's image in the eyes of residents of Baghdad to this day.

The Maragha Observatory was built on top of a hill outside the town of Maragha. It was remarkable with respect to five features: its financial administration; its astronomical instruments; its length of life and comprehensive observational program that culminated in a new and improved *zij*; its enormous library; its scholarly activity in astronomy. These characteristics became a model for many observatories to follow. As for the financial administration of the observatory, endowment, or *waqf*, revenues towards its building or maintenance, was first established by Hulegu.[35] At the Maragha Observatory, and with the personal encouragement of al-Tusi, a new tradition was set for funding observatories.[36] The Maragha Observatory was the “first Islamic observatory

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[34] Aydin Sayili, *The Observatory in Islam*, p. 202.

[35] *Waqf* was “a permanent and inalienable endowment which was completely harmonized with religious law and Moslem ideologies” (Sayili, p. 207); its funds assisted in sustaining charitable public institutions such as mosques and hospitals.

[36] Sayili, *The Observatory in Islam*, p. 208.

which benefited from *waqf* revenues".[37] Such funding of a public scientific institution allowed for the creation of a center for scholarship whose fame attracted scientists from many regions in the east and the west that contributed to what George Saliba called the Maragha Revolution.

As chief astronomer, al-Tusi brought together many scholars for the construction of the observatory. Those were al-Urdi (from Damascus), al-Maraghi, al-Akhlati (from Anatolia), and al-Qazwini.[38] Al-Urdi's contribution was especially significant because he was a renowned engineer who built accurate, large scale astronomical instruments for the observatory. His book, *Risalat al-rasd* (A Treatise on the Construction and Use of Observational Instruments), included a detailed account of those astronomical instruments he built for the Maragha Observatory.[39] One of the instruments he described and illustrated is a large mural quadrant.[40] It is an instrument that spans an angle of ninety degrees, where each degree was graduated down to the minute.[41] The quadrant was used for determining the latitude of Maragha. Sayili lists the Maragha Observatory instruments that were constructed by al-Urdi for astronomical observations.[42] Including the mural quadrant just described, there was an armillary sphere with five rings that was used to determine fixed stars coordinates.[43] In addition, there was an instrument with two holes for measuring the apparent diameters of the sun and the moon, and the sine and

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[37] For a detailed description of the financial administration of the Maragha Observatory, see Sayili 1960, 207-211.
[38] Rashiduddin, *Jami u*'*t-tawarikh (Compendium of Chronicles)*. English translation by W.M. Thackston. (Harvard: Harvard University Department of Near Eastern Languages and Civilizations, 1999), p. 502.
[39] Sevim Tekeli, *Al-Urdi's Article on "The Quality of Observation"*, (Manchester, UK, FSTC, 2007).
[40] See Figure 3, page 77.
[41] Ibid., pp. 7-9.
[42] For a complete list of astronomical instruments recommended for the Maragha Observatory by al-Urdi, see Sayili 1960, pp. 199-200.
[43] See Figure 4, page 78.

versed sine instrument (for measuring the azimuths and the sines of the angles of elevation). There is also reference to a surviving metallic celestial sphere that was constructed at the Maragha Observatory by Muhammad ibn Mu'ayyad al-Din al-Urdi (the son of the abovementioned al-Urdi).[44] This celestial sphere is now housed in Dresden.[45] After the construction of the observatory was completed, al-Urdi (d. 1266) remained for the rest of his life in Maragha as one of the permanent scientific staff at the observatory.

Maragha was the first observatory that had a life span of over fifty years during which it became an international institution that drew scientists from east and west. Sources inform us that Hulegu brought to Maragha many Chinese astronomers who carried with them knowledge of Chinese astronomy and of the Chinese calendar.[46] We know the name of one of them, Fao-Mun-Ji, although no details are available regarding his specific work at the observatory.[47] These astronomers introduced the *Zij-i Ilkhani* to China.[48] In addition to the astronomical observations, the *Zij-i Ilkhani* included calendars. According to Allsen, this is the evidence for the international collaboration that took place at the Maragha Observatory.[49] In al-Tusi's *zij*, he included "tables on the Chinese-Uighur calendars [that] were continuously reproduced in the eastern Islamic world until the end of the sixteenth century."[50] The calendar systems in western Asia were numerous and were based on different computational systems. Allsen informs us

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[44] See Figure 5, page 79.
[45] Sayli,*The Observatory in Islam*, p. 195.
[46] Sayli,*The Observatory in Islam*, pp. 205-206.
[47] Joseph Needham, *Science and Civilization in China*, (Cambridge, MA, The University Press,1961), p. 218.
[48] Sayli,*The Observatory in Islam*., p. 207.
[49] Thomas T. Allsen, *Culture and Conquest in Mongol Eurasia*, (Cambridge: Cambridge University Press 2001), p. 174.
[50] Ibid., 175.

that the Chinese material was introduced to prepare conversion tables that would give the equivalence of dates among the different calendrical systems.

> [The *Zij*]contains conversion tables for the calendars of the Greeks, Arabs, Chinese, Jews, Christians, and Persians. In the *Zij*, Tusi, by way of illustration, converts the date 1203 of the twelve-year animal[51] cycle into the appropriate Chinese, Eastern Christian, Muslim, and Persian dates.[52]

These conversion tables were used for administrative purposes by the Mongols. Thus, the first international multi-calendrical conversion tables were prepared at the Maragha Observatory.

It is important to note the caliber of the scholars employed at the Maragha Observatory, for it is their contribution to the science of astronomy that gives credence to what historians refer to as the Maragha Revolution. Amongst the impressive list of scientists at the Maragha Observatory was al-Maghribi.[53] He made significant contributions towards the completion of the astronomical tables, *Zij-I Ilkhani* (also known as *Ilkhani Tables*), which was the main achievement associated with the Maragha Observatory. The compilation of the *Ilkhani Tables* was completed on a preliminary basis in 1271.[54] However, after the death of al-Tusi in 1274, al-Maghribi made additional corrections, bringing them to completion and produced a z*ij* based on his own observations.[55]

One of the contributing factors that made the Maragha Observatory so impressive was the library it housed. It is said that its library contained over 400,000 volumes

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[51] The twelve-year animal cycle refers to the years of the Rat, the Rooster, the Snake, etc.
[52] Ibid., 164.
[53] For a complete list of all the scientists employed at the Maragha Observatory, see Sayili 1960, 205-207.
[54] Sayli,*The Observatory in Islam*, p. 204.
[55] Saliba,1983. An Observational Notebook of a Thirteenth-Century Astronomer. Isis, 74, (1983), p. 392.

brought to the observatory from Baghdad, Syria and al-Jazira. This collection attracted scholars from far away lands.[56] With its large and diverse staff of scientists, and an enormous library, Sayili declares the Maragha Observatory as an outstanding institution.

> With its large scientific staff and its huge library, the Maragha Observatory was thus not only an institution for research in astronomy, but it also had the characteristics of a scientific academy with excellent opportunities for scientific contact and exchange of ideas.[57]

a. The Maragha Revolution

The *Zij-i Ilkhani* produced at the Maragha Observatory was impressive. So, too, was the long-lasting influence of the Maragha Observatory. The Maragha School astronomers set research in astronomy on a new trajectory, described by Saliba as the Maragha Revolution. Namely, these astronomers introduced a new "philosophical dimension that was equal in importance to the mathematical and astronomical dimensions if not more so, and which was in the realization that astronomy ought to describe the behavior of physical bodies."[58]

This philosophical dimension allowed for the permanent departure from the Ptolemaic model. This model described celestial bodies in which the orbs of the celestial objects were mathematical rather than physical. Ptolemy had allowed for a celestial object to move around a circle, called an epicycle, whose center moved along another circle called the deferent. The deferent, in turn, moved about a hypothetical point that was off-center (called the equant) which was a physical impossibility. It was no longer

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[56] Sayli,*The Observatory in Islam*, p. 205.
[57] Ibid., p. 207.
[58] Ibid., p. 256.

sufficient for the astronomers at Maragha to have a mathematical description of celestial motion that fit observations, but it had to also match what was physically possible. This was evident in the new mathematical theorems the Maragha astronomers invented in order to correct Ptomely's equant problem.

From the middle of the thirteenth century, we begin to witness what Saliba refers to as "the Golden Age of Arabic astronomy."[59] It was during this time period that several attempts were made to find solutions to the difficulties in the Ptolemaic model of the heavens. Saliba makes a very important conclusion regarding the new tradition that came out of the Maragha School of thought:

> The Aristotelian division of motion in the universe as being only circular or linear was not altogether true, for one could very well produce linear motion by applying circular motion only, as in the case of the « Tusi Couple ».[60]

Until al-Tusi provided a complete proof of a theorem that became known as the Tusi Couple, it was believed that motion, whether terrestrial or celestial, was either purely linear or purely circular, respectively.[61] Thus the Tusi Couple created a dramatic departure from Aristotelian natural philosophy.

b. Tusi's Breakthrough and Legacy

Al-Tusi's theorem was fully stated and proved in his book *al-Tadhkira fi ilm al-hay'a* (Memoir on Astronomy) that he published in 1260. He applied his couple to his model of the upper planets in order to solve the problem of Ptolemy's equant, but still

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[59] Saliba, *A History of Arabic Astronomy*, p. 252.
[60] Saliba, *A History of Arabic Astronomy*, p. 256.
[61] For a detailed description of the Tusi Couple, see Figure 6, page 80.

account for observational results.[62] He successfully did so using spheres that rotated uniformly about their centers. “The success of this theorem had widespread repercussions. It ended up being used by almost every serious astronomer that followed Tusi, including the Renaissance astronomers, such as Copernicus and his contemporaries.”[63]

Al-Tusi’s *Tadhkira* presents a physical account of the universe, using a textual structure.[64] This view was a departure from the Ptolemaic model of the heavens that were purely mathematical. F. J. Ragep describes the uniqueness of the work in *Tadhkira.* It gave an overview of astronomy without including the cumbersome proofs the interested reader could easily find in Ptolemy’s *Almagest*. There was, of course, one exception, where al-Tusi provided a detailed mathematical proof of his well-developed theorem.[65]

Tadhkira had a widespread effect on astronomy everywhere. Ragep comments on this point by stating: “I suspect that from the thirteenth until the eighteenth centuries, the *Tadhkira* was the text of choice for beginning students of astronomy as well as educated laypersons who wanted an introduction [to astronomy].”[66] Ragep also informs us that *Tadhkira* became the primary source for future work in astronomy that spread beyond the borders of the Islamic world into Europe.

> Further west, the impact of the *Tadhkira* may also be detected. This was originally, but rather obliquely, suggested by Dreyer in a footnote in the

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[62] The upper planets then included Mars, Jupiter and Saturn.
[63] Saliba, *Islamic Science,* p. 158.
[64] F. J. Ragep, *Nasir al-Din al-Tusi’s Memoir on Astronomy (al-Tadhkira fi ilm al-hay’a),* (New York: Springer-Verlag, 1993), pp. 24-25.
[65] Ibid., II.11 of *Tadhkira,* p. 194-201.
[66] Ibid., p. 56.

> course of his discussion of Tusi’s models that referred the reader to Book III, Chapter 4 of Copernicus’s *De revolutionibus*, where the Tusi couple is introduced.”[67]

Based on the presentation above, it is evident that al-Tusi played a key role in the scientific development of astronomy. Even though al-Tusi had developed his non-Ptolemaic model before arriving at Maragha, it was there that he compiled his *Tadhkira*, and through contact with other astronomers at the observatory, participated in the exchange of ideas and in influencing them, thus creating a monumental stepping stone for others to follow.

The other astronomical innovation that was developed by a Maragha astronomer was Mu’ayyad al-Din al-Urdi (d. 1266). He was also attempting to solve the problem of the equant sphere rotating uniformly about a point outside its center. He proposed a new theorem, independently of al-Tusi, known as Urdi’s Lemma.[68] He used his new theorem to reconstruct Ptolemy’s model for the upper planets, but did so differently than al-Tusi. However, al-Urdi arrived at the same conclusion as al-Tusi; he used spheres that moved uniformly about axes passing through their centers. Thus, al-Urdi managed to avoid the use of the Ptolemaic equant, “but did not avoid accounting for its essential observational effects.”[69] Therefore, al-Urdi’s construction for the upper planets served to correct the equant problem.

Qutb al-Din al-Shirazi (1304-75) was the pupil of al-Tusi at Maragha. He followed his teacher’s example in re-constructing Ptolemy’s geocentric models based on physical reality. For that purpose, he utilized al-Urdi’s Lemma to provide new

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[67] Ibid., p. 57.

[68] For a detailed explanation of Urdi’s Lemma see Figure 7, page 81.

[69] Saliba, *Islamic Science*, pp. 132-232, esp. p. 202.

mathematical constructions of models for the upper planets as well as for the moon, while he relied on Tusi's Couple for his model of the planet Mercury.[70] Al-Tusi, al-Urdi, and al-Shirazi represent the pioneers of what became known as the "Maragha School" tradition.[71]

The ideas constructed by the Maragha Observatory astronomers continued to travel to different parts of the world long after the observatory went into ruins. The influence of those ideas set an entirely new tradition in mathematical astronomy that culminated in the work of the Damascene astronomer Ibn al-Shatir (d. 1375). He constructed astronomical models for the upper planets, Mercury, Venus, and the moon that corrected for, and aligned Ptolemy's representations with, the physical reality of rotating spheres. Ibn al-Shatir's models were all based on uniform circular motion of spheres orbiting about their centers. The equant problem was forever solved as Ibn al-Shatir demonstrated.[72] In his model for the upper planets he used Urdi's Lemma;[73] in planet Mercury's model he used the Tusi Couple. His models were different than those produced by al-Tusi, al-Urdi or al-Shirazi before him. In contrasting the work of Ibn al-Shatir with Ptolemy's, E. S. Kennedy and Victor Roberts conclude that "Ibn al-Shatir was the first we know thus far whose accomplishments were even remotely capable of

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[70] Mercury was then grouped into the lower planets that also included Venus.

[71] Roberts, "The Planetary Theory of Ibn al-Shatir" p. 210.

[72] The celestial objects known at the time were the sun, the moon, Mercury, Venus, the upper planets (Mars, Jupiter and Saturn) and the stars. Ptolemy had provided a mathematical description of the sun's motion based on physical reality (in other words, without using an equant). For all other celestial objects, Ptolemy had to resort to the use of the equant that was not physically possible). Not until Ibn al-Shatir do we find a comprehensive description of all celestial objects that could fit physical reality.

[73] Ibid., pp. 204-205. For an illustration of Ibn al-Shatir's model for the upper planets see Figure 8, page 82.

competing with those of Ptolemy in real science, that is, the precise description of natural phenomenon."[74]

The Maragha School tradition was extended well into the fifteenth and sixteenth centuries by the work of many astronomers. Ala' al-Din al-Qushji (d. 1474) was one such example; he developed a model that solved Mercury's equant problem that was different than the ones developed by al-Shirazi and Ibn al-Shatir. In his model he relied fully on Urdi's Lemma and seems to have been aware of al-Shirazi's Mercury model. Saliba informs us that while al-Shirazi believed his construction for Mercury had summed up the "one *true* mathematical model," al-Qushji was fully aware that he offered an alternative model in his treatise on planet Mercury.[75] This is significant because with al-Qushji we begin to see a departure from defining mathematical models as the truths representing reality, rather, they are tools of expressing physical phenomenon. This view matured fully with the astronomer Shams al-Din al-Khafri (d. 1550) who produced four different mathematical models describing Mercury's motion that were all equivalent, and all accounted for observations. Saliba goes as far as stating that al-Khafri was demonstrating how mathematics is but a linguistic tool.

> Seen as a tool, mathematics in the hands of Khafri would become just another language of science, a tool to describe physical phenomena, and nowhere required to embody *the truth* or the *correct* representation, as was apparently thought by Shirazi before.[76]

All astronomers within the Maragha School tradition were focused on finding solutions to the Ptolemaic equant problem. In his book, the *Takmila*, al-Khafri

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[74] E. S. Kennedy and Victor Roberts, "The Planetary Theory of Ibn al-Shāṭir," *Isis* 50, no. 3 (1959), pp. 227-235.

[75] Saliba, *Islamic Science*, p. 166.

[76] Saliba, *A History of Arabic Astronomy*, p. 167.

announced that he was continuing in the line of the work started by the Maragha Observatory astronomers. The other two astronomers mentioned above, namely Ibn al-Shatir and al-Qushji, relied directly on Tusi's Couple and Urdi's Lemma in their constructions. This places all three of them solidly within the tradition associated with the Maragha Observatory.

c. Transmission of the Maragha Model Westward

In Europe, the astronomical innovations imported from the east were not merely mathematical, as we shall see in this section; they also included the concept of the observatory that was almost identically modeled after the successors of the Maragha Observatory, specifically the Samarqand and Istanbul observatories.

In mathematical astronomy, the focus will be on Nicolaus Copernicus (1473-1543). Like his predecessors, Copernicus was preoccupied with the problem of the equant present in the Ptolemaic model. He considered the uniform rotation about the off-center point of the equant as a "defect" in the Ptolemaic system.[77] Similar to Ibn al-Shatir, Copernicus incorporated both Tusi's Couple and Urdi's Lemma into his planetary models. In fact, these were the only two new theorems that differed from the Ptolemaic models Copernicus addressed. According to Saliba, a close comparison between Ibn al-Shatir's model for the upper planets and that of Copernicus yields the same model "with the additional transportation of the center of the universe to the sun."[78]

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[77] Edward Rosen, *Three Copernican Treatises*, (NY: Dover Publications, 2004), p. 57.

[78] Saliba, *Islamic Scienc*, p. 204.

In *De Revolutionibus,* Copernicus attempted to resolve the Ptolemaic problems in Mercury's complex orbit. Saliba states that Copernicus used a theorem that is in essence the same as al-Tusi's theorem for Mercury's complex orbit, "and produced a very similar proof … without mentioning that he had invented the theorem or the proof himself, nor that he had seen it in any other source."[79] Saliba also mentions that Copernicus "stressed the simple mathematical feature" of al-Tusi's theorem in his *De Revolutionibus,* Book III chapter 4, and later on in Book V, chapter 32 he used the theorem to produce linear motion from circular motions "in his construction of the Mercury model."[80] Hartner goes as far as suggesting and demonstrating the similarities between Copernicus's theorem and that of al-Tusi's Couple in the lettering of the diagrams used by both astronomers.[81]

Copernicus' lunar model, as Kennedy informs us, "is greatly superior to the Ptolemaic one" and "is that of Ibn al-Shatir."[82] This, Kennedy adds, holds true for the Mercury model as well "with a small difference in vector lengths."[83] Kennedy concludes that "Copernicus was strongly influenced by the work of these people [Ibn al-Shatir, al-Tusi and al-Urdi].

Copernicus's mathematical representation of the orbits of the moon, Mercury, and the upper planets were virtually the same as those by Ibn al-Shatir where he used Tusi's Couple and Urdi's Lemma in the same fashion Ibn al-Shatir did in order to solve the

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[79] Ibid., p. 199.
[80] George Saliba, "Revisiting the Astronomical Contacts Between the World of Islam and Renaissance Europe: The Byzantine Connection," *Occult Sciences in Byzantium,* ed. Paul Magdalino, Maria Mavroudi, La Pomme D'Or, 2006, pp. 361-373, esp. 365.
[81] Willy Hartner, "Copernicus, the Man, the Work, and Its History," *Proceedings of the American Philosophical Society* 117, no. 6 (1973), pp. 413-422.
[82] E. S. Kennedy, "Late Medieval Planetary Theory," *Isis,* 57, no. 3 (1966), pp. 365-378.
[83] Ibid., p. 377.

same Ptolemaic problems. These similarities, in a sense, portray Copernicus as one who continued in the tradition of Arabic astronomy.

Copernicus is credited for the reintroduction of the heliocentric hypothesis, which was first proposed by Aristarchus of Samos (310-230 BCE). Saliba states that "there is no difference, from a pure mathematical point of view, between the centrality of the sun, or the earth." Furthermore, Saliba points out that ancient "astronomers have always known that astronomical phenomena observed from earth could be explained by holding earth stationary in the center and moving the sun, or vice versa."[84] Aristarchus' heliocentric theory was dismissed only because it lacked a cosmological frame to support it. The cosmological model that persisted from Aristarchus until Newton was the Aristotelian one, namely that an object naturally seeks the center of the earth so it could be at rest. Physical evidence to support such a model was plentiful, and Newton's alternative cosmological theory based on gravity did not yet exist. In his *De Revolutionibus*, Copernicus only suggested "new hypotheses."[85] This was in reference to his heliocentric model, since he did not offer any new cosmology; on the contrary, Copernicus was a strict adherer to Aristotelian cosmology as did his predecessors.

While today we attach great significance to the heliocentricity of Copernicus, to him this was not the real issue; it was mathematics. The bulk of Copernicus' *De Revolutionibus* was the mathematical treatment of the motions of the heavenly objects.

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[84] George Saliba, *Arabic Scientific Thought (al-Fikr al-Ilmi al-Arabi)*, (El-Koura, Balamund University, Lebanon, 1998), p. 103. The Arabic text I translated above is the following:

"و يجب أن نضيف هنا أيضاً أن لا فرق بين مركزية الشمس للعالم أو مركزية الأرض من الناحية الرياضية البحتة التي كان بعمل عليها هؤلاء الفلكيون. فلقد كانوا يعرفون تمام المعرفة أن الظواهر الفلكية التي نراها من الأرض يمكن أن تفسر على أن الأرض ثابتة و الشمس متحركة، أو بالعكس."

[85] Nicolaus Copernicus, *De Revolutionibus*, (Encyclopedia BritannicaInc., Chicago, 1952), pp. 499-838, esp. p. 506.

His concern with correcting the mathematical errors in Ptolemy's models, and his lack of concern with a new cosmological theory, presents Copernicus as an extension of the Maragha School tradition. I argue that Johannes Kepler was the first to depart from the Maragha School tradition. He was the first astronomer who abandoned the Greek's circular orbits, and the uniform motions. Hence it would be appropriate to refer to a Keplerian Revolution instead of a Copernican Revolution.

Not only did the Maragha Observatory set precedence in being an international research institution, it became a model for later observatories. It housed large astronomical instruments that would provide more accurate observations; it enclosed an enormous library, and it was built at a permanent location (as opposed to observation posts that were often relocated). In addition, the Maragaha observatory had a long thirty-year program of observation in order to observe the full cycle of Saturn. It also included a full program of observations, which included the sun, moon, the planets, and the stars that culminated in an astronomical *zij*. Previous observatories were short-lived and had limited their observations to a few celestial objects. There are two other important aspects of the Maragha model: its administrative organization under the leadership of a director, and its source of funding that guaranteed continuity of the work at the site. Even though the Mongol rulers did not spend their own funds on Maragha, they created the allocation of *waqf* (or endowment) funds to finance the observatory. This was, in essence, an indirect way of state-funding of an observatory. We shall see future observatories that were founded with the support of state or royal funds.

2. Later Islamic Observatories

a. Samarqand Observatory

The two Islamic successors of the Maragha Observatory that are important in the context of this discussion are the Samarqand and Istanbul observatories. They featured many of the characteristics of the Maragha Observatory. The Samarqand Observatory was founded, and funded, in 1420 by the governor of the region, Ulugh Bey, who became the director of the observatory.[86] In comparison to the fifteen or more astronomers at Maragha, the Samarqand Observatory had a staff of half as many, including the later addition of the young Ala' al-Din al-Qushji who was Ulugh Bey's pupil. The actual period of observation at Samarqand was a little over thirty years and an astronomical table (*zij*) was prepared. Some of the observatory staff came from far away, such as Qadizada who had come from Bursa in Turkey. The Samarqand Observatory, according to Aydin Sayili, was of great importance "both as a scientific institution and from the standpoint of its historical function."[87] As the "high watermark of Islamic achievement in this field of activity," in the fifteenth century, the Samarqand Observatory "constituted the most important link between Islam and Europe in the transmission of the tradition of founding observatories."[88]

b. Istanbul Observatory

The Istanbul Observatory was the third most important observatory in Islam, and is another example of a state-funded observatory. It was founded by the Ottomans based

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[86] Samarqand is in current day Uzbekistan.
[87] Sayili, *The Observatory in Islam*, p.259.
[88] Ibid., p. 259.

on the request of Taqi al-Din who had been a judge in Egypt prior to becoming the head astronomer at this observatory. Apparently, Taqi al-Din had explained to the Grand-vizier, Soqulla Muhammad Pasha, that the astronomical tables at the time were outdated and new observations were required in order to meet practical daily needs.[89] The site chosen for the observatory was in the European part of Istanbul, and the construction of the observatory and its instruments were completed in 1577, with Taqi al-Din as director of the observatory. This was one of the largest observatories of Islam, comparable to the Maragha and Samarqand observatories. Following the international model of the Maragha Observatory, we find mention of a correspondence in 1577-78 between Taqi al-Din and a Jewish astronomer who was in Salonica in Greece. Taqi al-Din corresponded with him regarding an eclipse that occurred but could not be observed in Istanbul that year. Accoding to Sayili, the Jewish astronomer, David, “may have joined the staff [at the Istanbul Observatory] in or after 1577-1578.”[90] The Istanbul Observatory was short-lived; it was demolished in 1580 due to a political rivalry. However, particular astronomical observations were recorded during its short life span. This was accomplished by utilizing a diverse collection of astronomical instruments housed at the observatory.[91]

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[89] Ibid., p. 289.

[90] Ibid., p. 297.

[91] For a detailed list of observations and instruments at the Istanbul Observatory, see Sayili, 1960, 298-300).

3. Early European Observatories

a. Kassel Observatory

The Kassel Observatory (1532-1592) was the first European observatory comparable to the Islamic ones. It was founded in 1560 by Landgrave Wilhelm IV of Hesse, and therefore is classified as a royal (or state-sponsored) observatory. Sayili informs us that the Kassel Observatory was "the first European observatory which was elaborate enough to be compared with those of Islam."[92] Kassel at the time was a center for astronomical research, and the observatory was the first permanent observatory of Renaissance Europe. Landgrave of Hesse was not merely a patron of astronomy, but contributed to the astronomical work at the observatory by conducting his own observations and cataloguing them.

b. Tycho Brahe Observatory

It was also upon Wilhelm's instigation that King Frederick II of Denmark decided to create the Uraniborg Observatory and patronize the astronomer Tycho Brahe as the director of the observatory. Thus, Tycho Brahe's observatory, located on the Island of Hveen, was a royal, state-sponsored observatory.

There were many parallels and common features between European observatories and those of Islam. Sayili tells us they were all concerned with instruments that had increasing precision, hence building larger and more accurate quadrants; they also

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[92] Ibid., p. 342.

depended on a fixed location of an observatory due to the large size of the instruments.[93] In addition, both Islamic and European observatories had to secure funding through state or royal support for the building of the observatory and the instruments, and for securing the continuity of work at the site. The observatory had the common administrative feature of having a director. Landgrave was himself an astronomer as well as a patron of other astronomers. Another similarity was the nature of the scientific work conducted in them. These overlapping characteristics between early modern European observatories and Islamic observatories suggest, according to Sayili, a "tangible historical continuity between them."[94]

Tycho Brahe's observatory was built before the invention of the telescope. With respect to its observational program and instruments, his observatory kept a medieval outlook; however, it was the last observatory to use instruments such as the parallactic ruler and the armillary sphere, that extends back to the time of Ptolemy. Thus, Tycho Brahe's observatory marked an important turning point in the history of observatories. Yet, there was still continuity between Brahe's observatory and other European ones to come.

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[93] A quadrant is graduated into ninety degrees. Each degree is subdivided into sixty minutes. A larger quadrant could also have each minute subdivided into sixty seconds, hence, further increasing the accuracy of the quadrant as an observational instrument.

[94] Ibid., p. 344.

IV. TRANSITION TWO: INTRODUCTION OF THE TELESCOPE TO THE OBSERVATORY

1. Seventeenth-Century European Observatories

By the middle of the seventeenth century many European observatories were founded. Some are still in operation. The Leiden Observatory was built in 1632; it had a royal origin and was attached to Leiden University. Denmark had a new observatory by 1637. The Copenhagen Observatory was a royal one as well, established by King Christian IV (son of Frederick II), and was attached to Copenhagen University. The Paris Observatory was built between 1667 and 1672; it was founded by King Louis XIV at the insistence of his Finance Minister, Jean Baptiste Colbert. The Royal Observatory in Greenwich, England, was founded in 1675, by royal decree. These observatories all had one thing in common: interest in increasing the accuracy of observational instruments and in obtaining new first-hand observations. The continuity is thus easily traced between Islamic observatories and the first modern observatories of Europe.

It is possible that Galileo realized, when he pointed his telescope to the heavens, he was beginning a new age of astronomical research. By Galileo, the telescope was first utilized in observing the heavenly objects in 1609; such observations were mostly of physical phenomena. Galileo observed blemishes on the sun, which became known as sunspots. The moon seemed to have a surface topography similar to our planet, and planet Venus exhibited phases not unlike our moon. These observations not only poked holes at the ancient theory of the heavens being perfect and separate from planet earth. They also confirmed that the earth could not possibly be at the center of the solar system.

Galileo's observations and their implications shattered beliefs dating back to ancient Greece. However, it was not until the invention of telescopic sight and the micrometer that the telescope actually ushered in a transition in observational astronomy. This shift occurred with the founding of the Paris Observatory. These inventions increased the accuracy of telescopes and made possible "the dreams of the astronomers of Islam or of Tycho Brahe."[95] The Paris Observatory housed observational instruments that were old and new. In addition to quadrants, octants, celestial globes and armillaries, the observatory had four telescopes equipped with micrometers. The new innovations applied to telescopes would lead to future ones that would transform the observatory into a new type of institution.

Jean Dominique Cassini joined the Paris Observatory in 1669. He was of Italian descent and was born and raised in Italy. He was educated at a Jesuit college in Genoa, where he studied astronomy. After he became the chair of astronomy at the University of Bologna in 1650, the Pope invited him to Rome, where he could use his engineering problem-solving skills. Astronomy, though, was Cassini's passion. He observed and documented the solar eclipse of 1661 and 1664, as well as the comets of 1652 and 1665. Cassini published a full report of these observations that included a study of the planets. This item brought Cassini fame in neighboring countries. When King Louis XIV of France decided to found the Paris observatory, he invited Cassini to direct the observatory. Cassini accepted the invitation of the king of France and lived on the second floor of the building of the observatory. Elizabeth Connor informs us that "Four

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[95] Sayili, *The Observatory in Islam*, p. 325.

generations of Cassinis occupied these rooms, and until 1794 the history of the Paris Observatory was largely the history of the Cassini family."[96]

Cassini was interested in using the telescope to search for new stellar objects and phenomena in the heavens that were invisible to the naked eye. Cassini is credited for discovering several moons of Saturn; in 1671 he discovered Iapetus using a telescope seventeen-foot in focal length. By the time the Paris observatory was completed in1672, Cassini discovered Saturn's fifth moon, Rhea, using the thirty-four foot telescope provided by King Louis XIV. The last two moons of Saturn were discovered by Cassini in 1682; he did so using larger telescopes measuring 100 and 136 feet in focal length. During the time the Cassini family was at the head of the Paris Observatory, the Paris Observatory was still mainly occupied with the observations of phenomena and the measurements related to positional astronomy; hence the telescope, as Sayili informs us, "administered efficiently to the long-standing needs" of the observatory as an "institution."[97] It is interesting to note that the Paris Observatory was founded for the pure study of astronomy, and astrology was excluded from its scope of activities. In fact, during the first half of the seventeenth century, astrology ceased to be associated with the study of astronomy.

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[96] Elizabeth Connor, *The Cassini Family and the Paris Observatory*, Astronomical Society of the Pacific Leaflets, Vol. 5, 1947, p. 148.
[97] Sayili, *The Observatory in Islam*, p. 327.

2. The Royal Observatory at Greenwich

Many of the seventeenth century European observatories were established in response to the need for more accurate navigation methods. The problem of determining longitude at sea was particularly urgent for reasons of safety and due to the competition among European countries in creating colonies across the oceans. It was under such circumstances that the Royal Observatory in Greenwich was founded. Decreed by King Charles II, the observatory was established by Rev. John Flamsteed who became the first Astronomer Royal in 1675. In order to determine longitude at sea a sailor would need to know local time at his location at the moment when the sun was at the highest point in the sky. However, the best clocks at the time were pendulum clocks and those would have been useless at sea. Flamsteed suggested using lunar observations to find longitude; this method is summarized by Sir Harold Spencer Jones, Astronomer Royal of the Greenwich Observatory in 1943.

> The Moon, being the nearest celestial body to the Earth, moves pretty quickly across the sky relative to the stars. We can consider the sky as a clock face and the Moon as a hand that moves across it. The position of the hand gives the time. The time cannot be read directly, but we can select some standard meridian and compute, for different times on this meridian, the distances of the Moon from adjacent bright stars. Then, if at any place these distances are measured, we can infer (after suitable corrections have been made to the observations) the time on the standard meridian.[98]

Flamsteed's suggestion would mean creating new lunar tables that would give the moon's position with an accuracy of less than half a minute of an arc. In addition, Flamsteed pointed out that new observations would be needed of the fixed stars and the motion of

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[98] Sir Harold Spencer Jones, *The Royal Observatory, Greenwich*, (London: Longmans, Green and Co., 1946), p. 3.

the Moon. The King thus decreed that "he must have them anew observed, examined and corrected, for the use of his seamen."[99]

Although he was given a prestigious position as the head of The Royal Observatory, Flamsteed had the difficult task of running an observatory with no instruments and no assistants. In addition, he was provided an inadequate stipend of ₤100 a year. Flamsteed was forced to tutor pupils privately in order to supplement his modest salary. He was expected to finance the purchase of his own observational instruments. It is remarkable that in the first thirteen years, while he worked alone, he collected 20,000 observations with a few instruments he had financed, which included a sextant of a seven-foot radius. Upon his father's death, Flamsteed was able to purchase a large mural arc with which he completed his observations by 1689. Flamsteed was able provide an enormous body of observations with considerable accuracy. According to the later Astronomer Royal, Sir, Harold Spencer Jones, Flamsteed "has aptly been called the first great English observer."[100]

Flamsteed's instruments gradually became more sophisticated as the instrument makers became more sophisticated in skill. After his sextant of seven feet in radius, he acquired a three-foot quadrant, and two telescopes.[101] Flamsteed later added a few other instruments, including "an object-glass of 90 feet focus."[102] He supplied Isaac Newton with observations of the moon's positions; Newton, at the time, was attempting to deduce

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[99] Ibid, p. 3.
[100] Sir Harold Spencer Jones, *The Royal Observatory*, p. 5.
[101] See Figure 8, page 82.
[102] Henry C. King, *The History of the Telescope*, (New York, NY: Dover Publications, Inc., 1955), p.63.

a theory of the moon's motion and needed the best available observational data. By the time of his death, Flamsteed had catalogued the positions of nearly three thousand stars.

In 1720, Edmond Halley succeeded Flamsteed at the Greenwich Royal Observatory. Halley was perhaps most known for his calculations that determined the comets of 1531, 1607 and 1682 were the same comet, and that it would return again in 1758. Harold Spencer Jones informs us that "the comet was first detected on Christams Day, 1758."[103] Halley also made the first southern star catalogue in 1677 from the south Atlantic island, St. Helena. He accomplished his task with the use of "a 5 ½-foot radius sextant, a 2-foot quadrant, two micrometers, a pendulum clock, and a 24-foot telescope.[104] With a grant from the Board of Ordnance, Halley was able to obtain "a meridian or transit telescope of 5 feet focus and 2 inches aperture."[105] This telescope granted him readings with an accuracy of about five seconds of arc.

The next few Royal Astronomers of the Greenwich Royal Observatory left a significant mark in the history of astronomy. James Bradley succeeded Halley in 1742; he was credited with the discovery of the phenomenon of light aberration. When a star is observed, it always appears displaced towards the direction in which earth is moving; this provided the first observational proof that earth is moving around the sun and not vice versa. In 1675, Nevil Maskelyne became director. It was during his tenure at the Greenwich Observatory that the marine micrometer was invented by James Harrison; this was the first instrument that kept relatively good time at sea. It was able to determine the longitude of Barbadoes within 16 minutes of arc. Maskelyne, however, preferred the

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[103] Jones, *The Royal Observatory, Greenwich*, p. 8.
[104] King, *The History of the Telescope*, p. 62.
[105] Ibid, p. 110.

method of lunar distances that gave the longitude of Barbadoes within a degree. Maskelyne maintained an extensive observational program for the sun, moon, planets and thirty-six fundamental stars; he became known as the “Father of Lunar Observations,” for he had provided corrections to the already improved lunar tables of Tobias Mayer, used in determining longitudes.[106] Maskelyne also determined the mean density of the earth, in other words he determined the ‘weight of the earth’ in 1774. Maskelyne was succeeded by John Pond in 1811; he compiled his observations of the stars in a catalogue that contained positions of 1112 stars completed in 1833. This was a most valuable contribution to astronomy during that period, and “few catalogues of that time can compare with it in accuracy.”[107] Within a few years of Pond assuming the Astronomer Royal position at Greenwich, control of the observatory transferred from the Board of Ordnance to the Board of Admiralty. This arrangement was more sensible since the observatory was closely connected with issues of navigation. It was under the Board of Admiralty, in 1822, that the number of staff members was increased from one to six, allowing observations to be continued for twenty-four hours. This transition completely shifted the observatory from a once royal observatory to a national one. The Greenwich Observatory became first in providing the public with a time signal using a five-foot diameter time-ball. The Admiralty published the following command in October 1833.

> The Lords Commissioners of the Admiralty hereby give notice, that a Ball will henceforward be dropped, every day, from the top of a pole on the Eastern Turret of the Royal Observatory at Greenwich, at the moment of one o’clock P.M. mean solar time. By observing the first instant of its downward movement, all vessels in the adjacent Reaches of the river, as well as in most of the Docks, will thereby have an opportunity of regulating and rating their chronometers.

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[106] Jones, *The Royal Observatory, Greenwich*, p. 16.
[107] Ibid, p. 18.

> The Ball will be hoisted half-way up the pole, at five minutes before one o'clock, as a preparatory signal, and close up, at two minutes before one.[108]

Noon mean time is different for different places; when we move one degree of longitude westward, noon time occurs four minutes later. In order to alleviate confusion in time associated with legal cases tried in court, "Greenwich Mean Time" became, in 1880, the "legal time of Great Britain."[109] This took place after George Biddell Airy was appointed Astronomer Royal at Greenwich in 1835. Airy took this a step further in 1865, after telegraphic communications had been developed. He had electric signals "sent to the Office of the Electric and International Telegraph," which then were "distributed over the railway network of the country."[110] This development eventually made Greenwhich Mean Time widely available.

Airy continued the work in positional astronomy, providing "more than 650,000 observations of the Sun, Moon, stars and planets."[111] This was done with Airy's Transit Circle; this was an instrument that combined characteristics of two previous instruments: the transit instrument and the mural circle.[112] Among many of his accomplishments, Airy established a solar department at the Greenwich Observatory in 1873. A photographing technique, known as photoheliograph, was introduced in order to obtain daily photographs of the sun. Sunspots had first been observed to vary periodically by the German astronomer Schwabe in 1851. With the new focus on sunspots, the Greenwich Observatory, at this point, was engaged in astronomical observations that were purely for

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[108] Ibid, p. 19.
[109] Ibid, p. 23.
[110] Ibid, p. 24.
[111] Ibid, p. 22.
[112] See Figure 9, page83.

research purposes in contrast with its initial practical mission in contributing to navigation.

It was under Airy's successor, Sir William Christie (who became Astronomer Royal in 1881) that the Greenwich meridian was chosen as the world's Prime Meridian in 1884. As a large national observatory, Greenwich contributed to astronomical research, especially after it acquired two major telescopes. Those were the 28-inch refractor used for observations of double stars, and the 26-inch photographic refractor mounted in 1894. After 1910, when Frank Watson Dyson became Astronomer Royal, a program for the measurement of temperatures of stars was established. Also, measuring stellar distances became possible by utilizing progressive photographic techniques. Additional research projects, and new observational instruments, maintained the international reputation of the Greenwich Observatory.

3. Early Observatories in the United States

The United States may have had a late entry into the science of observational astronomy; however, when it did enter, it launched itself into the field with extreme vigor. The oldest surviving observatory in the United States is the Hopkins Observatory at Williams College. It was founded by Professor Albert Hopkins. He visited England to purchase the necessary equipment for the operation of the observatory and formally opened it in 1838. In 1825, President John Quincy Adams told the US Congress:

> It is with no feeling of pride, as an American, that the remark be made that, on the comparatively small territorial surface of Europe, there are existing upward of one hundred and thirty of these light-houses of the

> skies; while throughout the whole American hemisphere there is not one.[113]

Perhaps the urging of President John Quincy Adams played a role in motivating the construction of the Hopkins Observatory. It is, though, interesting that by 1840 there were eleven observatories in America, and they were all equipped with observational instruments. Eight of the eleven observatories were considered public, as they were founded by educational institutions such as the Hopkins Observatory. It is important to note that all instruments equipping American observatories at that point were European-made. This was true of Dana House, the first observatory of Harvard College erected in 1839; most of its instruments were made in London. By 1847, it had added a fifteen-inch equatorial refractor, made by George Merz and Josef Mahler from Munich.[114] They were famous for their optical work. The 15-inch Harvard equatorial was the central feature of the Harvard College Observatory for a few decades. It is noteworthy to mention that the first national observatory was founded in 1842, in Washington DC, at the persistence of President John Quincy Adams. He convinced Congress to found a U.S. observatory. It was called the Depot of Charts and Instruments and had applied functional uses of astronomy to navigation. Later in the century it became the U.S. Naval Observatory. The second national observatory was established in 1890; it was the Smithsonian Astrophysical Observatory. This observatory was part of the Smithsonian Institution, founded by Congress in 1846.

Until about 1850, the only American astronomer who took interest in making instruments was David Rittenhouse (1732-1796). Prior to the existence of the first

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[113] Marlana Portolano, “John Quincy Adams's Rhetorical Crusade for Astronomy”, Isis, vol. 91, no. 3 (2000), pp. 480-503, esp. p. 488.

[114] See Figure 10, page 84.

permanent, public Hopkins Observatory, Rittenhouse had erected a small, amateur observatory in his home in 1769. This temporary observatory was located in Norriton in Philadelphia County, and its primary purpose was to observe the transit of planet Venus across the sun; it became known as the "Norriton Observatory."[115] After he moved to Philadelphia in 1770, Rittenhouse built a new observatory there. It is not clear whether Jefferson had designed the observatory that David Rittenhouse built in Philadelphia about 1783.[116]

V. TRANSITION THREE: ASTRONOMY RESEARCH AS A SCIENCE FOR THE SAKE OF SCIENCE

1. Probing the Heavens with a Spectroscope

It might have been a sore point for practical-minded Americans to rely on European large telescopes for their observatories, such as the Harvard refractor. This could have possibly motivated Alvan Clark, a portrait painter by profession who attempted to grind lenses and mirrors. He asked George Phillips Bond, the director of the Harvard College Observatory, to examine his telescope. Afterwards, Clark wrote:

> I was far enough advanced in knowledge of the matter to perceive and locate the errors of figure in their [Harvard College Observatory] 15-inch glass at first sight. Yet there errors were very small, just enough to leave me in full possession of all the hope and courage needed to give me a start, especially when informed that this object-glass alone cost $12,000.[117]

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[115] H. B. Rumrill, "Early American Astronomy", *Popular Astronomy*, vol. 50 (1942), pp. 408-418. (Courtesy Maria Mitchell Observatory, Provided by the NASA Astrophysics Data System).

[116] Marian C. Donnelly, Jefferson's Observatory Design, *Journal of the Society or Architectural Historians*, vol. 36, no.1 (1977), pp. 33-35.

[117] King, *The History of the Telescope*, pp. 246-260, esp. p.255.

The examination of the Harvard College Observatory telescope became a turning point in the career of Alvan Clark, although his fame would be made in England first, and was only to arrive back home in America later. Clark crafted two lenses, a 5 1/4-inch and an 8-inch lens; he used his lenses to observe double stars with his telescope. This occurred at a time when a Reverend in England was working on finding double stars. Rev. W. R. Dawes had great interest in astronomy and had a private observatory in Haddenham, Kent, that he equipped with a 6.5-inch Merz refractor. Clark contacted Dawes in 1851 disclosing his discovery of two double stars with his new lens. The news was so exciting to Dawes that he secured a telescope from Clark, to be followed later by four other purchases. According to Dawes, the 8-inch telescope he purchased "has afforded me some of the finest views of Saturn I have ever enjoyed."[118] Dawes discovered the inner ring of Saturn in 1850, simultaneously with W. C. Bond, the director of the Harvard College Observatory.

Clark's 8-inch lens that was mounted in Dawes's telescope passed into the hands of Sir William Huggins who did most of his pioneering work in astronomical spectroscopy with this Clark lens.[119] Such were the fruits of the Industrial Revolution as it was utilized in astronomy at the time. Like Dawes, Huggins had a private observatory; within a period of nine years, between 1860 and 1869 he did spectral analysis on stars using the Clark refractor, equipped with a two-prism spectroscope. Huggins was aware of the spectral analysis work done by Kirchhoff and Bunsen in 1859;

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[118] Ibid, p. 256.

[119] Spectroscopy is a science of analyzing the spectrum of colors in light emitted from a source. Kirchhoff had collaborated with his colleague Bunsen to design the first spectroscope. This consisted of a narrow slit, a first lens that can straighten the spreading light onto a prism, and a second lens that could magnify the emerging light spectrum coming out of the prism in order for it to be easily examined on a screen. See Figures 11 and 12, page 85-86.

they had mapped spectral patterns of different hot gases in the laboratory, and discovered that each element had its unique pattern of spectral lines. Huggins was interested in new methods of observation and was dissatisfied with ordinary astronomical work. The news had reached him regarding Kirchhoff's recent discovery of the chemical composition of the sun. Kirchhoff did this by interpreting solar spectral lines discovered earlier in the century by Fraunhofer, but in a new fashion. Upon this new discovery Huggins proclaimed:

> Here at last presented itself the very order of work for which in an indefinite way I was looking—namely, to extend his [Kirchhoff's] novel methods of research upon the sun to the other heavenly bodies.[120]

Even though Kirchhoff had applied his spectral analysis to the light of the sun, it was when Huggins extended this a technique to include all stars that astrophysics (the science of physics applied to astronomy) was truly born. In a paper written in 1864, Huggins compared stellar spectra with spectra of known elements in the laboratory. He concluded that "stars had elements in common with those of our own earth and had atmospheres like the sun."[121] Huggins applied similar techniques to a comet in 1868 and discovered that the comet's light "was due to luminous hydrocarbon vapour."[122] In that same year, Huggins was still attempting to determine the radial-velocity of certain bright stars like the star Sirius in the Canis Major constellation. Huggins had been familiar with the work of Doppler who, in 1841, had stated that the wavelength of light emitted from a star was altered by the motion of the observer relative to the star (towards or away). By 1872, Huggins was able to determine a radial-velocity of Sirius of about twenty miles per

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[120] King, *The History of the Telescope*, p. 285.
[121] Ibid, p. 285.
[122] Ibid, p. 289.

second relative to earth (a value close to modern calculations), with a shift of wavelength toward the red.[123] This meant that Sirius was receding from earth at that rate. This measurement, along with another important discovery by Huggins, would affect the trajectory of astronomy research from that point forward. Using his 8-inch Clark lens, Huggins discovered that nebulae that seem unresolved were "not an aggregation of stars [too distant to be resolved by current telescopes], but a luminous gas."[124] These findings would set the stage not only for future discoveries of galaxies outside our own Milky Way, but also of our expanding universe.

2. Lick Observatory

Let us now turn to the Lick Observatory. It was founded on Mount Hamilton near San Jose in 1888 by the California eccentric millionaire, James Lick. He wanted to finance the erection of "a powerful telescope, superior and more powerful than any telescope yet made."[125] He allocated $700,000 for the land purchase, building, and the construction of a 36-inch refractor telescope.[126] The observatory was initially operated by a small group of astronomers. J. E. Keeler was among the six astronomers in residence; he discovered the rings of Saturn within the very first nights the observatory had become operational in 1888. There were two important observational programs made possible by the 36-inch telescope. The first included determining the ratio of the

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[123] A star that would have its spectral lines shifted toward longer wavelengths (toward the red) would indicate that the star is moving away from an earth-bound observer, while a star with spectral lines shifted toward shorter wavelengths (toward the blue) would indicate a relative motion away from earth. This is known as the Doppler effect.

[124] King, *The History of the Telescope*, p. 286.

[125] Ibid, p. 308.

[126] See Figure 13, page 87.

number of observed stars to double stars, and the second was the radial-velocity program. In 1895, three years before Keeler would assume directorship, the observatory obtained a new 36-inch Calver-Common telescope from England; Keeler used it for photographic studies. It was the first large reflecting telescope in America, and the work Keeler did with this telescope would become "a landmark in the history of this instrument."[127] Compared to large nebulae like M31 in Andromeda and M33 in Triangulum, Keeler's photographs "revealed, for the first time, the existence of an immense number of either very small or very distant nebulae."[128] Until that moment, all stars and nebulae were thought of existing within the Milky Way. Keeler had discovered nebulae outside our Milky Way; though such extra-galactic nebulae were very remote, they were extremely numerous. These would eventually become known as galaxies.

A short historic perspective on astronomical photography is warranted at this point. Experiments with photographing the moon, the planets, and bright stars started in 1858; however, it was not until 1882 that David Gill (astronomer at the Royal Observatory, Cape of Good Hope) strapped an ordinary camera to his equatorial refractor and took photographs of the great comet of that year. Upon reviewing the photographs, Gill realized that, in addition to images of the comet, he had also obtained photographs of the background stars. Gill had simply embarked on a quick and new method of "constructing star maps free from personal error and the laborious methods of eye observation."[129] Astronomical photography went through many developments in the coming years, and by 1893 Dr. Boeddicker at Lord Rosse's Observatory had already

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[127] King, *The History of the Telescope*, p. 312.
[128] Ibid, p. 312.
[129] Ibid, p. 297.

provided photographs of the Milky Way. Prior to photographic images of it, drawings of the Milky Way were carefully prepared by Boeddicker and others. There were also drawings of other astronomical objects such as nebulae, which we now identify as galaxies.[130] It was quickly acknowledged that "the photographic Milky Way… can be mapped again and again during the time required to make a single complete drawing."[131] By 1897, E. E. Bernard at the Lick Observatory had taken photographs of the Milky Way that were "the *first photographs* made to show the structure of the Milky Way."[132] His photographs of the Orion nebula had revealed dark marking which were thought to be "obscuring masses of dust."[133] In addition, Bernard obtained evidence of filamentous nebulae which werestar clouds. Such clouds, we now know, are regions where stars are forming. According to King, the success of the work undertaken at the Lick Observatory "proved, beyond all doubt, the practicability of a large telescope situated at a high elevation."[134] This would soon be the model of Mount Wilson Observatory.

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[130] See Figure 14, page 88.

[131] Edward S. Holden, "Considerations on the Methods of Representing the Milky Way, suggested by a recent work", *Publications of the Astronomical Society of the Pacific*, vol. 6, no. 34 (1894), pp.24-30, esp. p. 30.

[132] A. A. Common, "Address on presenting the Gold Medal of the Society to Prof. E. E. Barnard", *Monthly Notices of the Royal Astronomical Society*, vol. 57 (1897), pp.321-328 esp. p. 325.

[133] King, *The History of the Telescope*, p. 301.

[134] Ibid, p. 314.

3. The Legendary Mount Wilson Observatory

a. George Ellery Hale and the Coming of Mount Wilson Observatory

The observatory built on Mount Wilson, near Pasadena, was initially thought to be temporary. An astronomical expedition to Mount Wilson was led by George Ellery Hale in 1904. Seven years earlier Hale had founded the Yerkes Observatory of the University of Chicago. At the time, Yerkes Observatory was the most modern observatory in the country; it was founded for research and observation, and was equipped with a 40-inch telescope. Hale was a visionary and a risk-taker. Before he was associated with the Yerkes Observatory, he was already engaged in research in astrophysics. Hale managed to persuade his father, and source of wealth, to finance the building of a 60-inch mirror to be cast in a telescope with the hope that it would become the largest telescope in the world. Little did he know that it would become the central tool in the future Mount Wilson observatory. When Hale had accepted the directorship at the Yerkes observatory, it was based on one condition, that he would donate his 60-inch mirror to the University of Chicago if the institution would finance the telescope the mirror would be mounted onto. They eventually failed, and Hale retrieved the 60-inch mirror back.

Hale built Yerkes as an observatory that would utilize research in physics and chemistry to advance astronomy and further his study of the sun. At the time of his Mount Wilson expedition, Hale was still the director of Yerkes Observatory. Earlier that year, he had received a small grant from the Carnegie Institution of Washington in the amount of $10,000. The funds appropriated by the Carnegie Institution would not have been sufficient to finance the building of a permanent observatory. The Carnegie Institution had among its new Board of Trustees members the astrophysicist, and Smithsonian director, Samuel Pierpont Langley. In 1903 Langley had suggested exploring the feasibility of building a temporary solar observatory on Mount Wilson. Hale, however, had other unofficially announced plans.

Having experienced unsatisfactory observing weather conditions in the upper Midwest, Hale envisioned a permanent solar observatory equipped with several telescopes on Mount Wilson. With little operational funds, Hale gambled with his own money and arranged to pay for the transfer of three Yerkes astronomers in early 1904. He also began the permanent installation on Mount Wilson later that year. His hopes were to establish a national solar observatory. Through his bold actions, he was able to convince the Executive Committee of the Carnegie Institution to finance his project. In a telegram he received on December 20, 1904, he learned that "the Executive Committee has appropriated $150,000 a year for two years and has authorized the immediate execution of the larger plan."[135] Thus began the story of the greatest astrophysical observatory in the world.

Mount Wilson observatory was funded by the private Carnegie Institution of Washington, established in 1904 by Andrew Carnegie. Carnegie was a poor Scottish immigrant who became a multi-millionaire. He wanted to create a center to promote new research in the United States that "will compare in the near future not unfavorably with

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[135] Allan Sandage, *Centennial History of the Carnegie Institution of Washington: Volume 1, The Mount Wilson Observatory: Breaking the Code of Cosmic Evolution*, (Cambridge: Cambridge University Press, 2004, p. 12.

those of any other lands."[136] With an endowment of $10 million he founded an institution that would soon make the United States a world leader in science. Though the Carnegie Institution was privately funded, its first Board of Trustees members were from various political, academic and scientific backgrounds. Among them were "Secretary of State John Hay; Elihu Root, who had been Secretary of War under President Theodore Roosevelt, and John Hopkins University President Daniel C. Gilman."[137] There were also five additional members in virtue of their official positions; those were "the president of the United States, the President of the Senate, the Speaker of the House of Representatives, the Secretary of the Smithsonian Institution, and the President of the National Academy of Sciences."[138] This great number of U.S. officials among the twenty-two members of the Board of Trustees would suggest the institution's plan of operation, including that of Mount Wilson Observatory, would have direct input from the country's governing body. This is reminiscent of the Maragha Observatory that was founded by Hulegu who represented the governing power of that region in Persia. Had Hulegu survived the first years of operation at Maragha, he would have had some influence over the program of observation at the observatory.

The name of Mount Wilson was named after the Tennessee pioneer Benjamin Wilson who, in 1864, was seeking wood from the mountains in order to make casks for the wine from his vineyards. Wilson had been a resident in the region, and had become "the second elected mayor of Pueblo de Los Angeles in 1851."[139] In his search for lumber, Wilson had set workers from his ranch to enlarge an old Indian trail up the

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[136] Ibid, p.29.
[137] Ibid, p. 30.
[138] Ibid, p. 30.
[139] Ibid, p. 15.

mountain; the task was completed in 1864. That year Wilson discovered that the wood was too porous for the wine casks and he abandoned the mountain, yet the trail remained in use as the shortest path to the mountain summit. The city of Pasadena was later founded in 1873, at the foothill of Mount Wilson.

Conditions for observations at the summit of Mount Wilson were excellent. There were several individuals who would have their eye set on Mount Wilson. It would take three attempts to build an observatory at the summit of that mountain before Hale would finally succeed in 1904. The University of Southern California (USC), founded in 1880, had received a $50,000 pledge from the wealthy E. F. Spence who was an astronomy enthusiast. Spence had considered the Lick Observatory, located in the San Francisco Bay area over 300 miles to the north, as one that had created an "astronomical coup."[140] Following in the footsteps of James Lick, Spence decided to fund a larger telescope for USC that would rival the 36-inch Lick refractor. Acting on such a pledge from Spence, the president of USC, Marion Bovard, went to Massachusetts to place an order for a 40-inch lens with the then famous lens-maker Alvan Clark and Sons. His plan was to build the world's largest refracting telescope to be placed on top of Mount Wilson as the centerpiece of the Spence Observatory. Much to Bovard's disappointment, Spence died in 1892 without making any arrangements for funding the observatory. The 40-inch lens was eventually bought by the University of Chicago's Yerkes Observatory that was founded by Hale that year.[141] At the time USC was initiating plans to build the Spence Observatory on Mount Wilson, the director of Harvard College, Edward C. Pickering, had similar plans of putting a 13-inch Harvard telescope on the summit of the mountain

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[140] Ibid, p. 25.

[141] See Figure 15, page 89.

in Pasadena. Pickering achieved his goal after making the trip west to assess the potential for a Harvard telescope on top of Mount Wilson, jointly with the Spence telescope. In 1889, the Harvard 13-inch telescope arrived at the summit of Mount Wilson. However, plans to build a major Harvard Observatory on Mount Wilson were eventually moved elsewhere to Arequipa, Peru. The third attempt at building an observatory at Mount Wilson coincided with the Spence and Harvard Observatory plans. Thaddeus Lowe was a self-educated man in several scientific fields; he had dreamed of putting an observatory at the top of Mount Wilson, after forming a partnership with David Macpherson who wanted to build a railway to Wilson's peak. Plans for the railway, and subsequently for the observatory, were derailed when the new Mount Wilson Toll Road had undergone construction. It is interesting to consider how the development of astronomical research might have followed a different path had any of those three observatories seen the light of day. Hale's vision of mounting the largest telescope on top of Mount Wilson would surpass Bovard's, Pickering's and Lowe's. He succeeded in raising sufficient funds to build two large telescopes for Mount Wilson's observatory; a 60-inch telescope completed in 1908 and a 100-inch Hooker telescope installed in 1919.[142] This was in addition to two tower telescopes, a 60-foot solar tower telescope in 1907 and a 150-foot solar tower in 1910.

The early research at Mount Wilson concentrated on the new field of astrophysics that applies physics principles, especially spectroscopy, to astronomy. Hale was particularly interested in spectral analysis of the sun rather than traditional astronomy, which concerned itself with studying star positions and motions. He had arranged to

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[142] See Figures 16 and 17, page 90-91.

borrow the Snow telescope, named after its benefactor Helen Snow, from Yerkes Observatory and moved it to Mount Wilson in its early months of operation. Soon after, the telescope became the permanent property of Mount Wilson Observatory. One of the earliest discoveries at Mount Wilson, using the Snow telescope, was the difference in temperature between sunspots and the surrounding regions of the sun's photosphere.[143] Charles Young, from Princeton University, had demonstrated differences between sunspots spectra in contrast to spectra from the sun's photosphere in 1893. Aware of Young's work, Hale and Walter S. Adams, along with astronomer Henry G. Gale (whom Hale had invited for a visit, from the University of Chicago, in 1908) demonstrated for the first time that sunspots had lower temperature than the photosphere. In addition, Hale stated in his 1908 paper titled "Solar Vortices" that there is "a single suggestion relating to the possible existence of magnetic fields on the sun."[144] Hale had noticed that the pattern of swirls around sunspots resembled the distribution of iron filings around the poles a magnet.[145] He determined the polarization of the double lines observed in sunspot spectra, known as the Zeeman effect, and discovered powerful magnetic fields in sunspots. This was the greatest discovery in solar physics at the time and it granted Hale a nomination for the Nobel Prize in physics. Other work was done at Mount Wilson using the Snow telescope. Adams made "the first spectrographic determinations of the Sun's rotation."[146] Adams also obtained the best measurements for demonstrating the sun's varied rotation with latitude, known as differential rotation. In a paper he published in 1925, Hale and Seth B. Nicholson discussed many of the sunspots observed

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[143] The photosphere is the only visible layer of the sun; it is also referred to as the solar disk.
[144] Sandage, *The Mount Wilson Observatory*, p. 65.
[145] See Figure 18, page 92.
[146] Sandage, *The Mount Wilson Observatory*, p. 67.

characteristics. Among them was the reversal of sunspot polarity from the northern to the southern hemisphere of the sun at any given time in the approximate eleven-year sunspot cycle. Hale stressed "the sharpness with which the equator separates spots of opposite polarity."[147] Furthermore, the polarities between hemispheres changes every sunspot cycle.

Every few years, new staffers would be added to Mount Wilson. Between 1912 and 1920, seven new appointments would take place that would change the tone of Mount Wilson Observatory from a strictly solar observatory to the diverse astronomical observatory it eventually became. Among the magnificent seven was Harlow Shapley, who arrived in 1914, and Edwin Hubble, who was appointed in 1919 to work in nebular studies. Not only did the new arrivals strengthen the solar program at Mount Wilson, they also "initiated the dominance of stellar and extra-galactic astronomy."[148] Although by 1948 only four percent of its publications were concerning galaxies and the universe, it was the content of those papers that became the foundation of observational cosmology, the true legacy of Mount Wilson Observatory. Nearly half of those papers were by Hubble who very quickly drew an overwhelming attention from the media.

b. Edwin Hubble and the Birth of Observational Cosmology

Edwin Hubble was a bright student at the University of Chicago where he completed both his undergraduate and graduate work, obtaining a PhD degree in 1917. He was highly recommended by his professors. Upon returning from the Great War,

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[147] George E. Hale and Seth B. Nicholson, "The Law of Sun-Spot Polarity", *Astrophysical Journal*, vol. 62 (1925), p.270-300, especially p. 298. See Figure 19, page 93.
[148] Sandage, *The Mount Wilson Observatory*, p. 88.

Hale offered him a position at Mount Wilson. Hubble had shown early signs of self-confidence which later engendered a lot of jealousy and even dismay. In his thesis, Hubble had used a classification of nebulae suggested by Max Wolf at Heidelberg in 1908. Hubble had commented that Wolf's classification system of twenty-three categories had no relationship between one another, hence it was "wholly empirical and probably without physical significance."[149] Furthermore, he stated that Wolf's scheme was temporarily excellent for "filing away data *until a significant* [italics mine] system shall be constructed."[150] By 1926, Hubble had himself constructed a remarkable new classification system of nebulae, which would become known as Hubble's "Tuning Fork."[151] In his system, he divided nebulae into two broad categories, regular and irregular nebulae. He further divided the regular nebulae into either elliptical or spiral. According to Hubble, the elliptical nebulae were designated by the symbol E; "they range from globular objects through ellipsoidal figures."[152] The round, globular objects were labeled with an E0, while ones with lenticular form were E7. The spiral nebulae, however, fell into two distinct sequences; those were the normal and barred spirals designated with the letters S and SB, respectively. At the beginning of its sequence, the spiral nebulae have arms that are tightly coiled about a bright central region, and somewhat resemble an E7 nebula. "As the sequence progresses, the arms increase in bulk, "while unwinding "until in the end they are widely open."[153] The spiral nebulae designation would progress through Sa, Sb to Sc. The barred spiral objects are similar to

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[149] Ibid, p. 483.

[150] Ibid, p. 483.

[151] See Figure 20, page 94.

[152] Edwin Hubble, *The Realm of the Nebulae*, (New York: Dover Publications Inc., 1958), p.39. See Figure 21, page 95.

[153] Ibid, p. 43.

the spirals, except for a “broad bar [that] has condensed diametrically across the nucleus.”[154] The barred spirals would be types SBa, SBb and SBc, progressively. As for the irregular nebulae, such as the Magellanic Clouds, they comprise about three percent of the total number; they lack the presence of a conspicuous nucleus and “show no evidence of rotational symmetry.”[155]

Hubble’s classification system would prove to be so superior such that it is still in use to this day. However, when Hubble created his classification scheme of nebulae, the debate had not been settled on whether those nebulae were within the Milky Way or were extra-galactic. Most astronomers in the late nineteenth and early twentieth century had the notion that the Milky Way was the universe and that all observed bright objects were contained within it. In an historic 1920 discussion, known today as the Shapley-Curtis debate, Harlow Shapley argued that spiral nebulae were relatively nearby objects within the Milky Way. On the other hand, Herber D. Curtis championed the extragalactic island universe hypothesis, arguing that each spiral nebula was its own rotating system of stars outside Milky Way. The debate was not settled because no one had any evidence that would demonstrate exactly how far away each spiral nebula was.

In 1922, Hubble published what became two classic papers in astronomy. In May of that year, Hubble published a brief introduction of his galaxy classification system that included galactic and nongalactic ones. He also included in that paper everything that was discovered about nebulae by other astronomers, such as Sir William Herschel and his son Sir John Hershel, Sir William Huggins, Vesto M. Slipher and others. These two

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[154] Ibid, p. 43-44. See Figure 22, page 96.
[155] Ibid, p. 47.

papers proved that he was a remarkable astronomer. Hubble was then elected to serve on the International Astronomical Union's Commission 28 on Nebulae. Slipher was presiding over the commission when it met in 1925, and although Hubble could not attend that meeting, he submitted a memorandum in which he was proposing an improvement to his 1922 classification scheme of galaxies. Slipher's response to Hubble's memorandum was damning. He criticized every point in Hubble's memorandum. As an additional insult to Hubble, Slipher included Shapley and Lundmark on Commission 28 immediately after the 1925 meeting. Both Shapley and Lundmark possessed strong views on classification, and Hubble considered Lundmark as having usurped his own classification scheme. When Hubble published his 1926 paper, he added the following in a footnote.

> K. Lundmark, who was present at the Cambridge [Commission 28] meeting and has since been appointed a member of the Commission, has recently published… a classification which, except for nomenclature, is practically identical with that submitted by me [to the Commission 28 in 1925.] Dr. Lundmark makes no acknowledgement or reference to the discussion of the Commission.[156]

Shapley had also introduced his own classification system which was complex, added nothing new, and had no physics behind it to. He would eventually abandon his own system years later. Sandage summarizes the fundamental difference between Reynold's (and Shapley's) classification system and that of Hubble's as follows: "Their work (John Henry Reynolds and later Shapley) failed to advance any ideas of the physics of galaxies based on a classification scheme with a continuous variation of a few parameters placed in a continuum. Remarkably, Hubble's system does just that."[157] When Hubble realized

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[156] Sandage, *The Mount Wilson Observatory*, p. 487.
[157] Ibid., p. 489.

that he would not find any genuine cooperation from the members of Commission 28, he struck out on his own and published his 1926 "Extra-galactic nebulae" paper. Hubble recognized his classification system to be superior because it was simple. In his reply to criticism by Reynolds in 1927, Hubble wrote that "a first general classification should be as simple as possible."[158] The relationship between Hubble and Shapley was mutually unfriendly. It is difficult to ascertain whether it was because the two scientists held very different galactic theories and one of them seemed favored by the Commission 28, or if it was something more personal. When Sandage once mentioned Shapley's name in front of Hubble, Hubble became dead serious. Sandage informs us that Hubble "spoke of Shapley's stubbornness, his penchant to draw speculative conclusions from inconclusive data, his overweening desire for publicity."[159] However, Hubble remained objective in his assessment of the star catalog Shapley devised with Ames, known as the *Shapley-Ames Catalog*. On this note, Hubble told Sandage "this is the best thing Shapley ever did."[160]

In order to prove that some nebulae were extra-galactic and do not belong to the Milky Way galaxy, a method to measure nebulae distances was very much in need. Hubble devised a method which utilized work done by Henrietta Leavitt between 1908 and 1912 on Cepheid variable stars in the Small Magellanic Cloud. According to Hubble, Leavitt had observed that “the brightest Cepheids had longer periods (pulsated more slowly) than the fainter Cepheids.”[161] In 1912, Leavitt published a paper in which she announced a direct (linear) relationship between the period the Cepheid star pulsated

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[158] Ibid., p. 490.
[159] Ibid., p. 492.
[160] Ibid., p. 492.
[161] Ibid, p. 15.

and its luminosity; dim Cepheids pulsate rapidly with periods of 1 to 2 days while the brightest ones pulsate slowly over 100 days. This relationship became known as the period-luminosity relation.[162] Hubble applied Leavitt's results to study the extragalactic nebulae M31, M33 and NGC 6822 arguing that

> The [period-luminosity] relation evidently reflected certain inherent characteristics of Cepheids which would presumably be found in all such stars wherever they might be located—in the Cloud, in the galactic system, or elsewhere. If the relation could be numerically calibrated… the Cepheids, since they are so readily identified, would furnish *a powerful method of estimating great distances* [italics mine].[163]

Thus the Leavitt's period-luminosity relation became a yardstick for measuring distances of nebulae containing Cepheid variable stars. There are four steps to determine the distance to a Cepheid star. The first step is to observe the pulsating period. Then, using the period-luminosity relation, the star's luminosity could be determined; this would provide the absolute magnitude of the star (which is directly related to the luminosity). Then we observe the apparent magnitude of the star, and finally we use the distance-magnitude relationship to calculate the distance.[164]

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[162] See Figure 23, page 97.

[163] Hubble, *The Realm of the Nebulae*, p. 15.

[164] Suppose we could place all stars at the same distance, we could obtain their absolute magnitudes, M; astronomers use the fixed distance of 10 parsecs in measuring absolute magnitudes of stars (one parsec is equal to 30.86 trillion kilometers, 19 trillion miles, or 3.26 light years). Absolute magnitudes range from M= -10 for the brightest stars to M= +17 for the dimmest. For example, our sun's absolute magnitude is M= +4.8. Absolute magnitudes are usually determined based on apparent magnitudes since we cannot move stars to a distance of 10 parsecs and then re-measure their magnitudes. A mathematical relationship between absolute magnitude, apparent magnitude and distance was determined from information of nearby stars; this was done in 1856 by the English astronomer Norman Pogson. The relationship was determined from observations of nearby stars; the apparent magnitude, m, of such a star could easily be determined, then the distance, d, would be calculated from the star's measured parallax angle. Combining those two, quantities would result in the absolute magnitude, M by using Pogson's relationship $M = m-5 \log (d/10)$, where "log" is the ten-based logarithmic function. For further information on the Pogson's calculation of stellar magnitude, consult D. Jones, "Norman Pogson and the Definition of Stellar Magnitude", Astronomical Society of the Pacific Leaflets, vol. 10, no. 469 (1967), pp. 145-152.

The first recognized variable star in an extragalactic nebula was reported in 1922 by J. C. Duncan; it was observed in the M33 nebula. By the end of 1924, and with the use of the 100-inch telescope, Hubble had found 36 variables in M31, "12 had been recognized as Cepheids, and the order of the distance fully established."[165] Similar investigations were extended to the M33 nebula and the NGC 6822 irregular nebula; 22 and 11 Cepheids were found in M33 and NGC 6822, respectively. With extensive analyses of the stars found in the three extragalactic nebulae, Hubble concluded that the nebulae "were clearly independent stellar systems."[166] This proved the existence of galaxies and their clusters of stars like our own Milky Way. The discovery of Cepheid variables in M31 and the other two nebulae as pointers to an exterior universe settled the Shapley-Curtis debate forever. According to Sandage, Hubble had demonstrated the "large-scale structure [of the universe] defined by galaxies." Hubble's success elevated his fame world-wide; however, his greatest success was yet to come.

c. Hubble's Expanding Universe

In 1916 Einstein expanded his special theory of relativity to include gravity, yielding his general theory of relativity. In his general theory, Einstein proposed that matter (with its gravitational effect) causes space to curve. When he applied his theory to the structure of the universe, his equation predicted the universe to be an expanding or a contracting one. This contradicted the prevailing contemporary model of a static universe. Einstein convinced himself that such results were irrelevant because stars move slowly compared to the speed of light. He, therefore, introduced a supplementary

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[165] Hubble, *The Realm of the Nebulae*, p. 93.
[166] Ibid, p. 100.

cosmological constant to his equations “for the purpose of making possible a quasi-static distribution of matter, as required by the fact of the small velocities of the stars.”[167]

The small radial velocities of nebulae were first measured in 1912 by V. M. Slipher at the Lowell Observatory in Flagstaff, Arizona. His first observations of the spectrum of M31 had revealed a velocity of 300 kilometers per second (190 miles per second) in a direction approaching us. Over the next decade, Slipher would observe radial velocities of forty additional nebulae, all positive velocities, indicating motion away from the observer on earth. Although Slipher carried out this work almost alone, there were other observatories confirming similar results. By 1925, there was a total record of forty five nebular velocities. Hubble informs us that despite the fact “the first velocity was negative, indicating motion toward the observer,” other nebulae with positive velocities “were found in increasing numbers, and soon they completely dominated the list.”[168] Hubble proceeded to confirm that such an observation would demonstrate the nebulae “were independent bodies and this conclusion was consistent with the theory of island universes [or galaxies].”[169] Hubble would next provide a new theory to explain the observed data and give rise to the most fundamental discovery in cosmology of all time.

Observation of nebulae radial-velocities was performed using spectral analysis of the light emitted from such nebulae. Upon obtaining emission spectra of nebulae, it was observed that spectral lines were slightly shifted toward longer wavelengths (known as

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[167] Norbert Straumann, *The History of the Cosmological Constant Problem*, Institute for Theoretical Physics University of Zurich, CH–8057 Zurich, Switzerland (2008), pp. 1-12, esp. p. 3. Invited talk at the XVIIIth IAP Colloquium: Observational and theoretical results on the accelerating universe, July 1-5 2002, Paris, France.

[168] Hubble, *The Realm of the Nebulae*, p. 105.

[169] Ibid, p. 105.

red-shift).[170] This would be consistent with a light-emitting source that is moving away from the observer, according to the Doppler Effect. Hubble examined the red-shifts in the nebulae emission spectra provided earlier by Slipher and later by Milton L. Humanson of Mount Wilson Observatory. He formulated a relationship between the velocity of observed nebulae and their measured distances; this became known as the velocity-distance relation.[171] When Humanson announced a very high measured velocity (or red-shift) for the elliptical galaxy NGC 7619, Hubble was convinced that his velocity-distance analysis was leading him to something fundamental. Hubble informs us that the "velocity-distance relation is… a general characteristic of our sample of the universe."[172] In 1929 he announced that the amount of red-shift was larger for the more distant nebulae, concluding that the more distant galaxies were moving faster away from the observer; Hubble had demonstrated an expanding universe, contrary to Einstein's static universe.

Hubble had formulated the velocity-distance relation as one where the radial velocity of nebulae was proportional to its distance. The proportionality constant came to be known as Hubble's constant; Hubble had determined the value of this constant as 550 kilometers per second per megaparsec. Today the Hubble constant, as measured by NASA's Chandra X-ray Observatory and Hubble Space Telescope is about 72±8 kilometers per second per megaparsec. This result gives an estimate for the age of our universe between 12 and 14 billion years.

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[170] See Figure 24, page 98.
[171] See Figure 25, page 99.
[172] Hubble, *The Realm of the Nebulae*, p. 120.

With his expanding universe theory, supported by a large sample of data, Hubble had set cosmology to dominate the scene of observational astronomy. This new science of observational cosmology became a leading current in astrophysics as astronomers search for the origin of our universe. “Some have said,” Sandage informs us, “that Hubble was the most influential astronomer since Copernicus in changing our view of the outside world.”[173]

VI. CONCLUSION

The observatory as an institution in its modern form, such as the observatory at Mount Wilson, goes back more than seven hundred years to the east, specifically to the Maragha Observatory. Observations of the heavens obviously extend back in time to the ancient cultures of Egypt and Babylon, among many others. However, the observatory as an institution underwent three major transitions. The first transition took place with the founding of the Maragha Observatory; Maragha set new standards for observatories that were followed by later ones until modern times. The second transition was ushered in with the introduction of the telescope into the realm of observational astronomy. The third main transition happened whenever observatories adopted observational programs that were pure research in nature, rather than serving the practical needs for which positional astronomy was applied.

The Maragha Observatory introduced the first transition; it played a significant role in the historical development of astronomy in several ways. Maragha provided an

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[173] Sandage, *The Mount Wilson Observatory*, p. 521.

opportunity for international collaboration and produced the first international multi-calendrical conversion tables. The Muslim astronomers at Maragha, such as al-Tusi, developed innovative mathematical theorems that were employed in correcting the flaws in the Ptolemaic models of the heavens. Tusi's Couple also eventually caused a revolutionary shift away from the once significant Aristotelian view, namely that all motion in the heavens is only uniformly circular. Other astronomers at Maragha, such as al-Urdi and al-Shirazi, gave rise to a new tradition in astronomy known as the "Maragha School." This new tradition extended the ideas founded in the thirteenth century into the fourteenth, fifteenth and sixteenth centuries. Later astronomers, especially Ibn al-Shatir, constructed mathematically correct models for all the planets and the moon, which were non-Ptolemaic; his models were the precursor of the Copernican ones. This, in a sense, portrays Copernicus as one who continued in the tradition the Maragha School. The Maragha Observatory historically served as a model of a research institution that influenced future observatories in the Islamic world and Europe. The Samarqand and Istanbul observatories were modeled after Maragha, and they in turn had a significant effect on the development of the early observatories in Europe, such as the Kassel Observatory and Tycho Brahe's observatories. They, in turn, influenced later European observatories which, in turn, influenced American ones. The Maragha Observatory set an example in many ways which included: founding a fixed location for observations that would house larger and more accurate instruments; funding for the observatory through royal or state support; creating a long-term observational program that extended more than thirty years and was comprehensive in observations of the planets, moon and stars; providing an administrative directorship example; and producing new astronomical tables as a culmination of the observations. It is left for future research to determine the true defining borders, if any, between Islamic and Renaissance observatories.

The application of the telescope to the heavens led to the second transition in the development of observational astronomy. Prior to the telescope, astronomy was mostly concerned with measuring the positions of the sun, moon, planets, and stars with increasing accuracy, using instruments such as the quadrant, sextant, and others. When the telescope was first aimed at the sky, Galileo made observations of the moon's surface that expanded the scope of astronomy. With his discovery of Jupiter's moons, it was possible to begin to extend the idea to the planets in our solar system orbiting the sun in a similar fashion. The telescope opened new channels of inquiry that could not have been possible before. Studies of physical phenomena exploded at the observatory scene as detailed images of known celestial objects revealed new features about them, such as Saturn's moons that were discovered by Cassini. Discoveries of new objects like double stars, Cepheid variable stars, and extra-galactic nebulae would not have been made possible without the telescope. These new objects begged an explanation, thus changing the history of positional astronomy. Although a revolutionary instrument, the telescope developed the same way as other astronomical devices. Just as medieval and Renaissance observatories were preoccupied with crafting larger and more accurate instruments, modern observatories were following in the same progression with building larger telescopes. This progress with the telescope could be easily traced; some of the early telescopes mounted in observatories were modest in length, such as the ones used by Flamsteed at the Greenwich Observatory. Telescopes gradually became longer like the eventual 136-foot telescope at the Paris Observatory. Telescopes began also to be equipped with new inventions, like micrometers, for accurate readings. With the increasing demand for higher resolution, new telescopes such as refractor and later reflector telescopes started to be developed, also with increasing size.

More telescope innovations further changed the nature of observation, and thus the mission of observatories. The dramatic shift from positional astronomy occurred with the use of telescopes equipped with spectrometers. Thus the third transition in the history of the observatory occurred. Spectrometers were devices that allowed for the knowledge in physics to be married to astronomy; this created the new science of astrophysics. These instruments allowed for observations of an entirely new kind of astronomy. We see the emergence of new fields such as the solar astronomy program at Yerkes Observatory; we also see the study of magnetism on earth extended to the sun in connection with sunspots, as we have seen with Hale at Mount Wilson. New spectroscopic analysis of starlight led to the determination of the stars temperature and chemical composition. These examples point to the new direction of pure research in astronomy. For the longest part of its history, astronomy had been mainly preoccupied with measuring positions of celestial objects, often to serve practical needs. The transition to pure astronomical research involved a new philosophical approach that was not concerned with practical needs, but propelled by a need for more knowledge. This opened the door for further fields in astronomy to emerge next to astrophysics. The application of photography to telescopes played an important role; images of our Milky Way prepared by Bernard at the Lick Observatory helped in understanding the structure of our galaxy. Images of extra-galactic nebulae made the task of comparing them easier for Hubble. This development led to his famous classification of nebulae. Also, with deciphering the coded messages embedded within Cepheid variables, Hubble was able to conclude that such nebulae were galaxies far away from our Milky Way. These discoveries led to the creation of the new science of cosmology. When Hubble coupled his study of galaxies with the Doppler Effect, he concluded that evidence existed suggesting an expanding universe; i.e. the further away we gaze into the universe, the faster the galaxies were moving apart. If we traveled backward along the timeline, the universe would be shrinking until we arrive at the moment our universe was born. This point marks the point in time that became known as the Big Bang, when the universe began to expand. There is perhaps one significant conclusion that resulted from turning to pure research: astronomers discovered the beginning of time.

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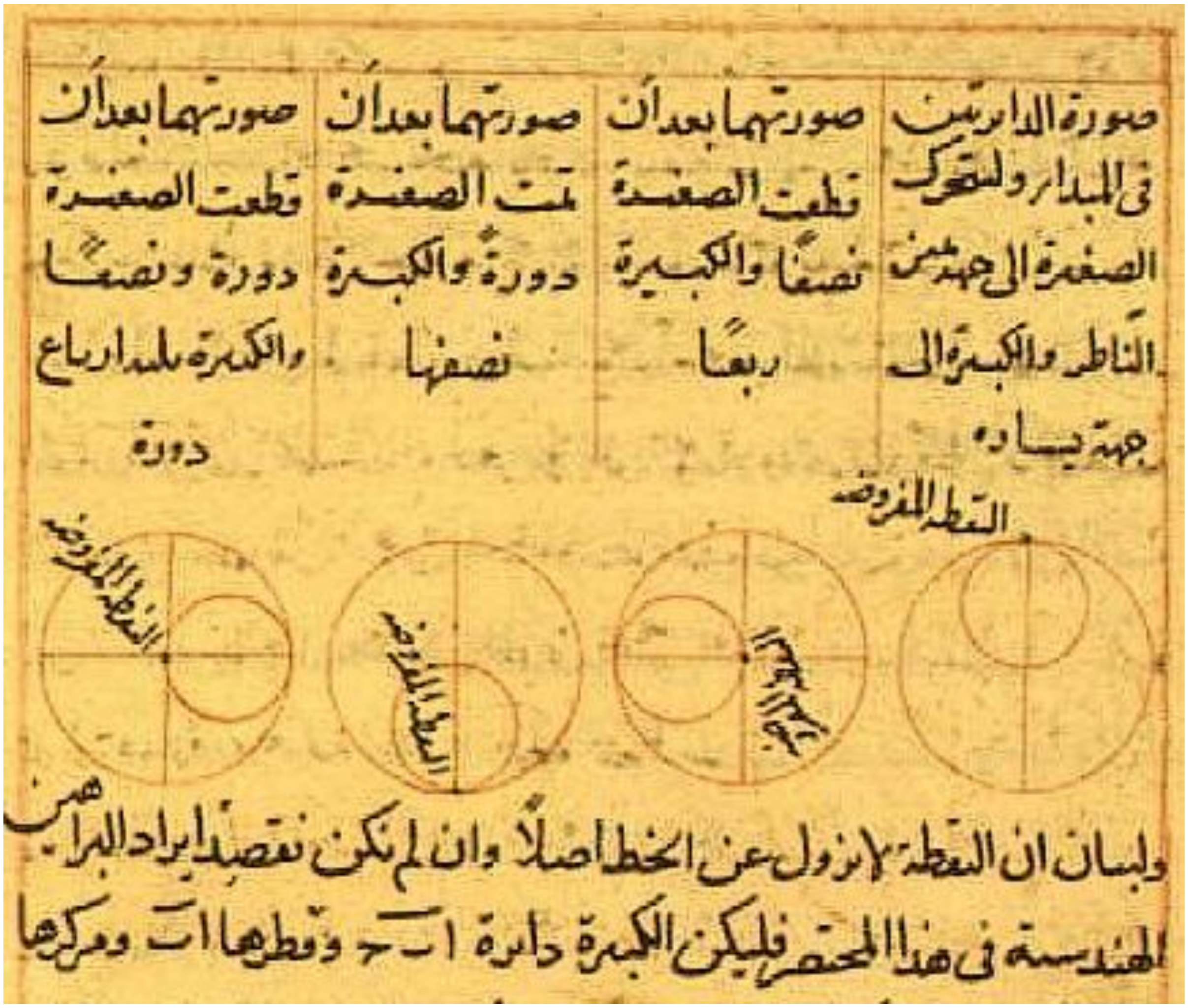


صورة الدائرتين في المبدأ ولتتحرك الصغيرة الى جهة يمين الناظر والكبيرة الى جهة يساره	صورتهما بعد ان قطعت الصغيرة نصفا والكبيرة ربعا	صورتهما بعد ان تمت الصغيرة دورة والكبيرة نصفها	صورتهما بعد ان قطعت الصغيرة دورة ونصفا والكبيرة ثلثة ارباع دورة

ولبيان ان النقطة لا تزول عن الخط اصلا وان لم نكن نقصد ايراد البراهين الهندسية في هذا المختصر فليكن الكبيرة دائرة ا ب ج وقطرها ا ج ومركزها

Figure 1

Diagram of Tusi's Couple as depicted in the thirteenth century Arabic MS 319 (folio 28v) held at the Vatican library. Tusi's Couple was invented by Nasir al-Din al-Tusi based on his theorem that converts uniform circular motion into linear motion. See Figure 6 for a complete statement of Tusi's Couple. From Ahmed Jabbar, *The Golden Age of Arabic Sciences*, Institute Du Monde Arabe, Damascus, 2008.

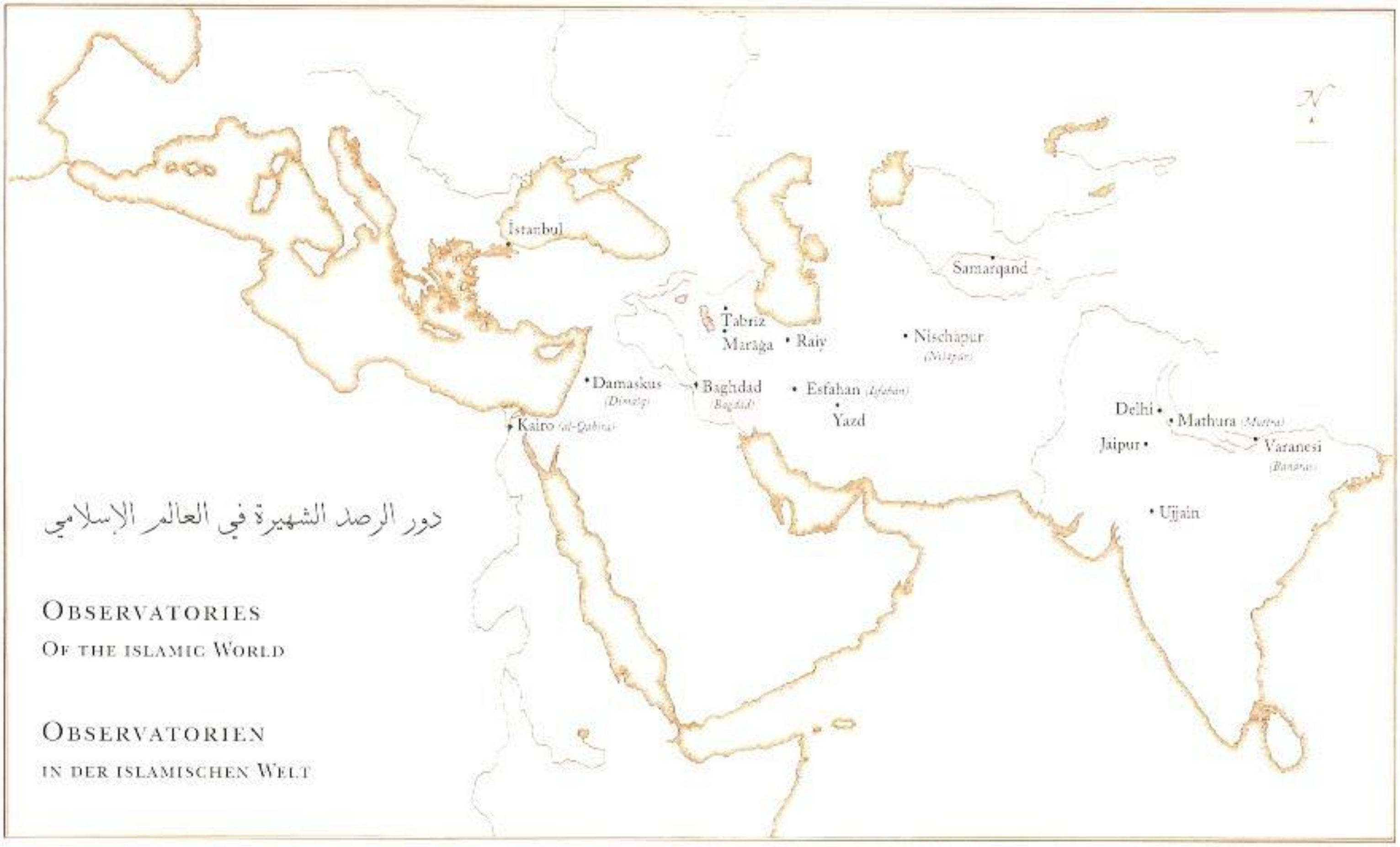


Figure 2

Map of the famous Observatories of the Islamic world. From Fuat Sezgin, *Science and Technology in Islam: Catalogue of the Exhibition of the Institute for the History of Arabic-Islamic Science* (at the Johann Wolfgang Goethe University, Frankfort, Germany), Frankfurt Book Fair 2004.

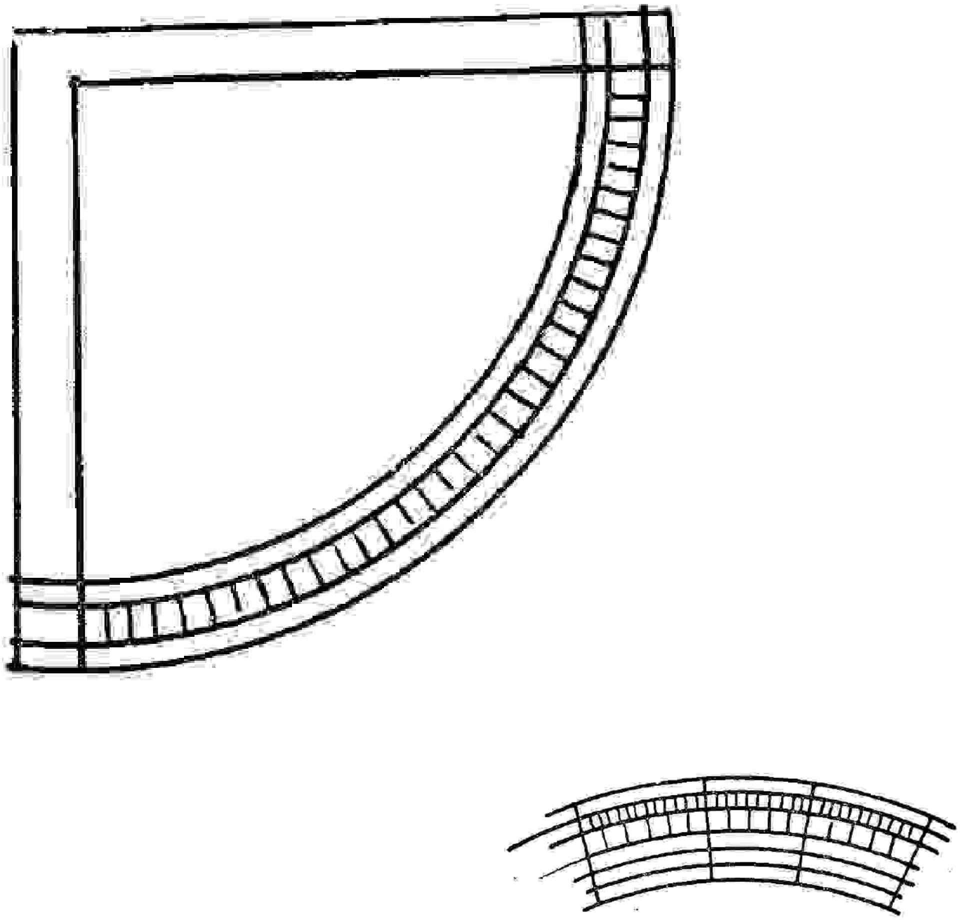


Figure 3

Illustration of the mural quadrant al-Urdi constructed at the Maragha Observatory. The quadrant is divided into 90 degrees and each degree is subdivided into 60 minutes. From Sevim Tekeli, *Al-Urdi's Article on "The Quality of Observation"*, Manchester, UK, FSTC, 2007.

Figure 4

Model of the armillary sphere from the Maragha Observatory. From Fuat Sezgin, *Science and Technology in Islam: Catalogue of the Exhibition of the Institute for the History of Arabic-Islamic Science* (at the Johann Wolfgang Goethe University, Frankfort, Germany), Frankfurt Book Fair 2004.

Figure 5

Model of the celestial sphere from the Maragha Observatory (the original is kept in Dresden since 1562). From Fuat Sezgin, *Science and Technology in Islam: Catalogue of the Exhibition of the Institute for the History of Arabic-Islamic Science* (at the Johann Wolfgang Goethe University, Frankfort, Germany), Frankfurt Book Fair 2004.

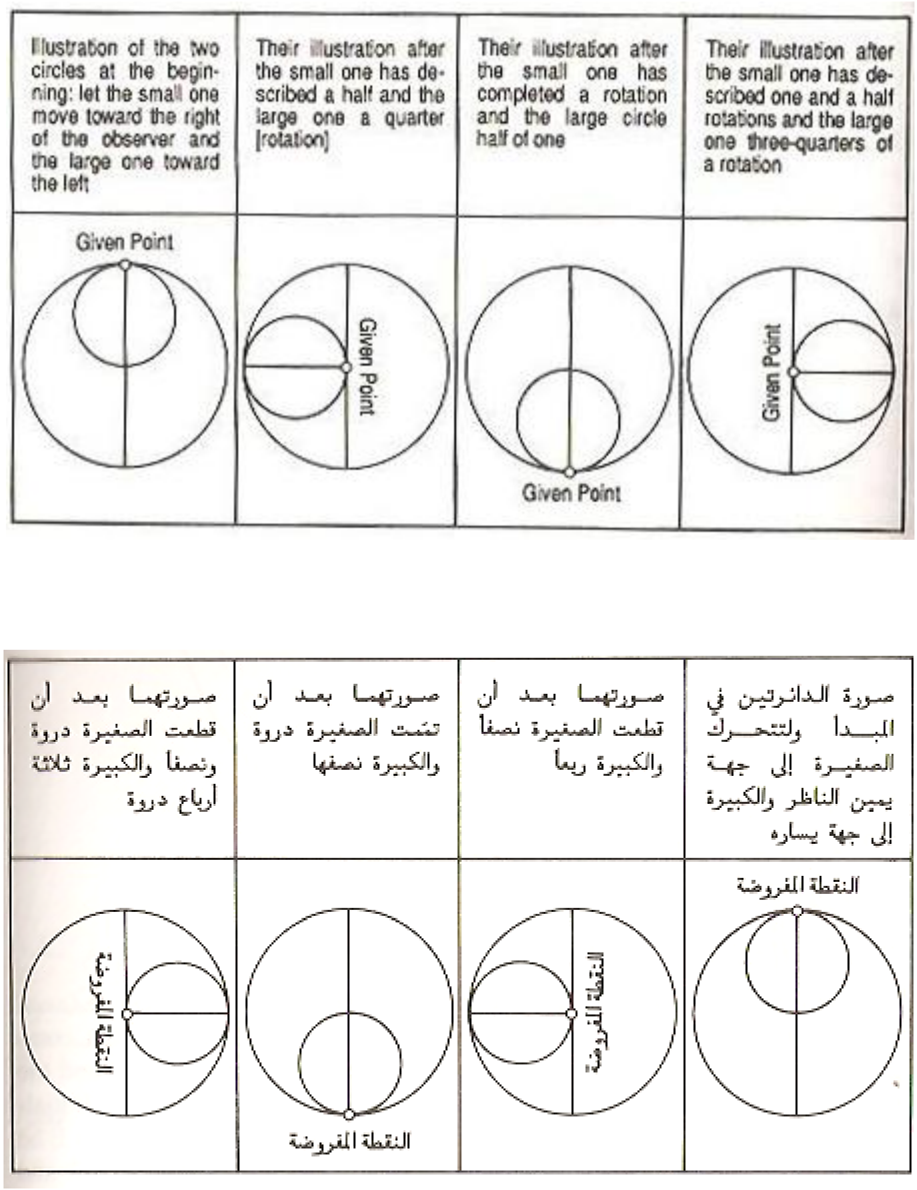


Illustration of the two circles at the beginning: let the small one move toward the right of the observer and the large one toward the left	Their illustration after the small one has described a half and the large one a quarter [rotation]	Their illustration after the small one has completed a rotation and the large circle half of one	Their illustration after the small one has described one and a half rotations and the large one three-quarters of a rotation

صورة الدائرتين في المبدأ ولتتحرك الصغيرة إلى جهة يمين الناظر والكبيرة إلى جهة يساره	صورتهما بعد أن قطعت الصغيرة نصفاً والكبيرة ربعاً	صورتهما بعد أن تمت الصغيرة دورة والكبيرة نصفها	صورتهما بعد أن قطعت الصغيرة دورة ونصفاً والكبيرة ثلاثة أرباع دورة

Figure 6
Statement of the Tusi Couple as stated by Naṣir al-Din al-Tusi in his book *al-Tadhkira fī ʿilm al-hayʾa* (F. Jamil Ragep 1993, 194-195). "If two coplanar circles, the diameter of one of which is equal to half the diameter of the other, are taken to be internally tangent at a point, and if a point is taken on the smaller circle—and let it be at the point of tangency—and if the two circles move with simple [uniform] motions in opposite directions in such a way that the motion of the smaller [circle] is twice that of the larger so the smaller completes two rotations for each rotation of the larger, then that point will be seen to move on the diameter of the large circle that initially passes through the point of tangency, oscillating between its endpoints.

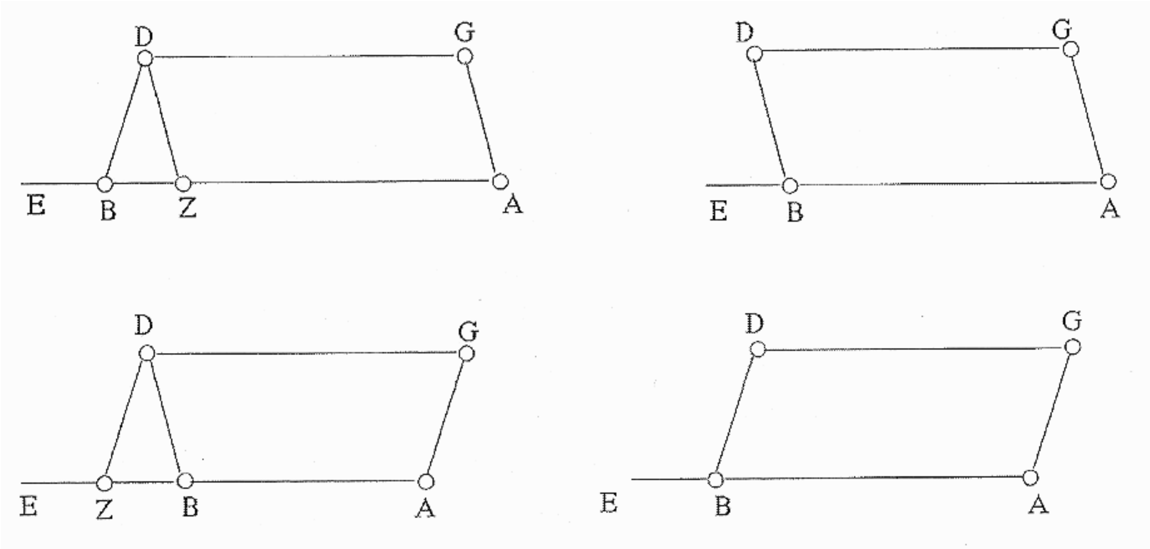


Figure 7

A general representation of the four cases of Urdi’s Lemma as it appeared in the original manuscripts. The statement of the Lemma, according to Saliba is as follows. For “any two lines (such as AG and BD) that are equal in length and that form equal angles with a base line AB, either internally or externally, the line DG, joining the other extremities of these two lines, is parallel to the base line AB.” This pictorial representation appeared in George Saliba, *Islamic Science and the Making of the European Renaissance*, (Cambridge, MA: MIT Press, 2007), p. 203.

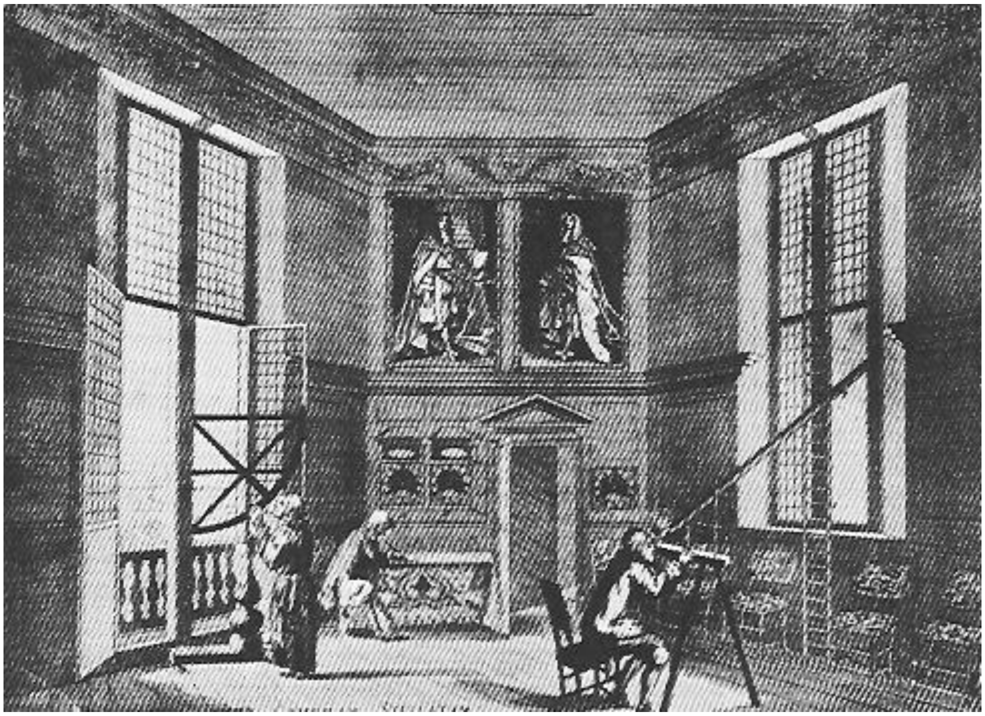


Figure 8

The Royal Observatory in Greenwich in Flamsteed’s time. Observers are shown with quadrant and telescope. This pictorial representation appeared in Henry C. King, *The History of the Telescope*, (New York, NY: Dover Publications, Inc., 1955), p. 63.

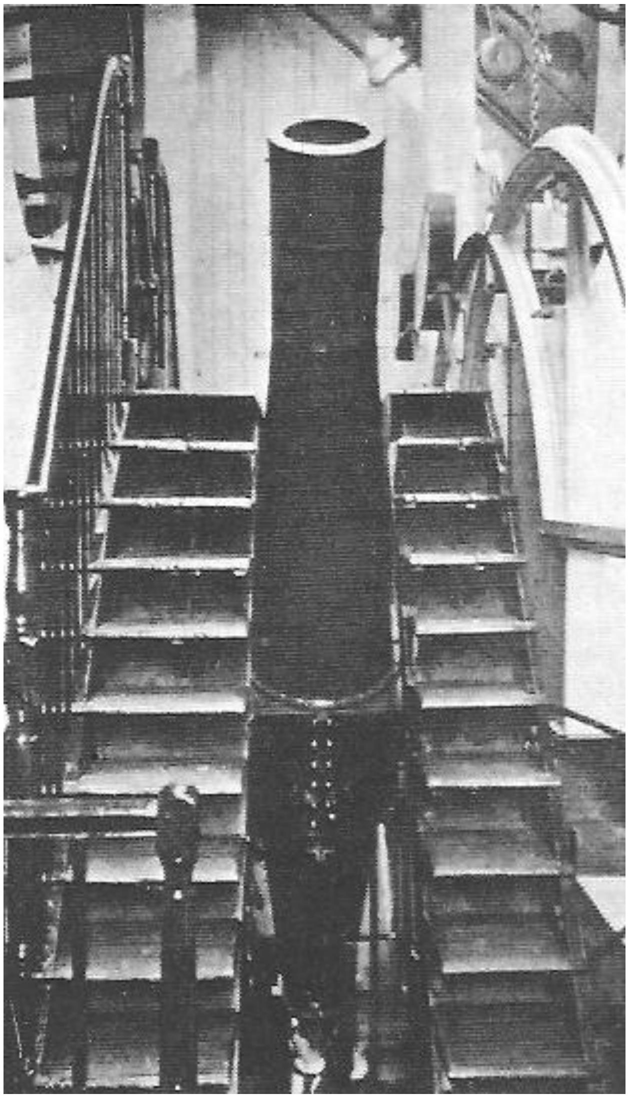


Figure 9

The Airy Transit Circle. This photo appeared in Henry C. King, *The History of the Telescope*, (New York, NY: Dover Publications, Inc., 1955), p. 241.

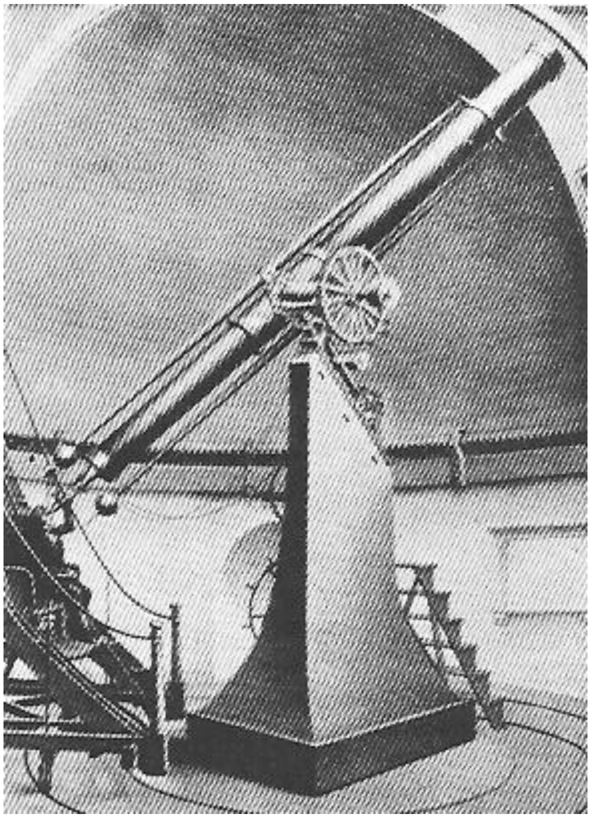


Figure 10

The 15-inch Harvard equatorial. This pictorial representation appeared in Henry C. King, *The History of the Telescope*, (New York, NY: Dover Publications, Inc., 1955), p. 249.

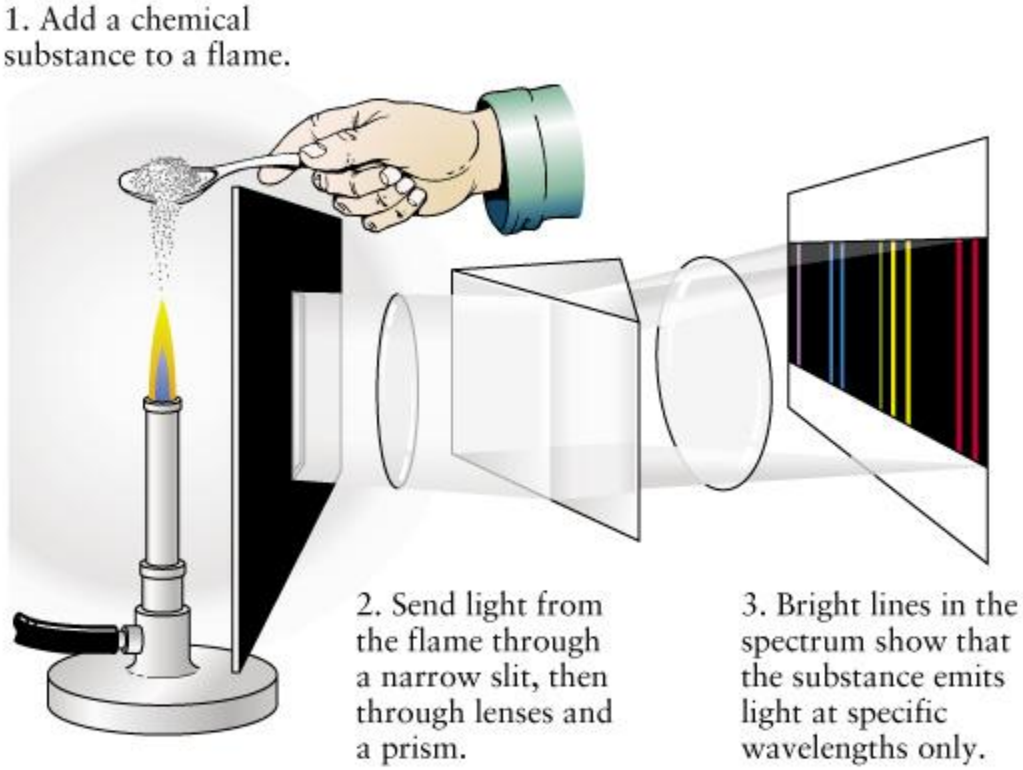


Figure 11

Early Spectroscope. “In the mid 1850’s Kirchhoff and Bunsen discovered that when a achemical substance is heated and vaporized, the resulting spectrum exhibits a series of bright spectral lines when passed through a slit, lenses and a prism. This device is called a spectroscope. In addition, they found that each chemical element produces its own characteristic pattern of spectral lines. The lenses focus and magnify the spectrum.” This pictorial representation appeared in Neil F. Comins and William J. Kaufmann III, *Discovering The Universe,* (New York: W. H. Freeman and Company, 2008), p. 110.

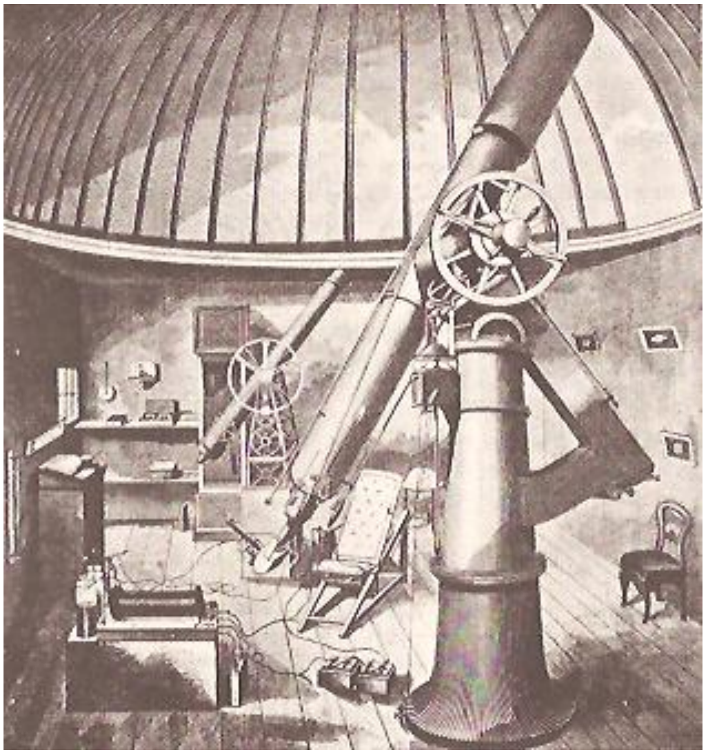


Figure 12

William Huggins' 8-inch Clark-Cooke equatorial refractor. This pictorial representation appeared in Henry C. King, *The History of the Telescope*, (New York, NY: Dover Publications, Inc., 1955), p. 286.

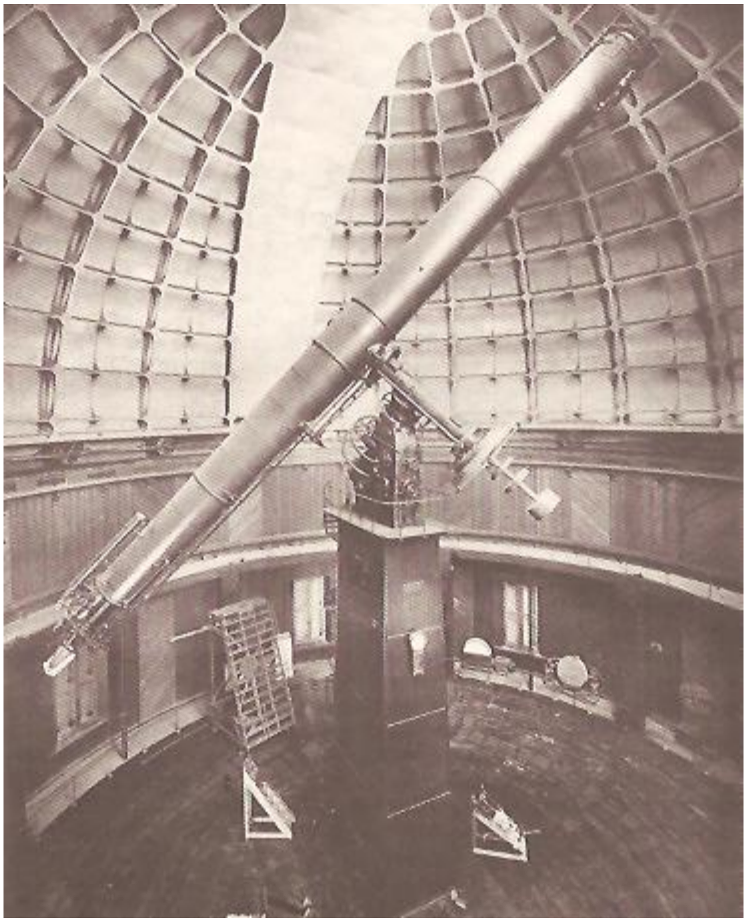


Figure 13

The 36-inch Lick refractor. This photo appeared in Henry C. King, *The History of the Telescope*, (New York, NY: Dover Publications, Inc., 1955), p. 313.

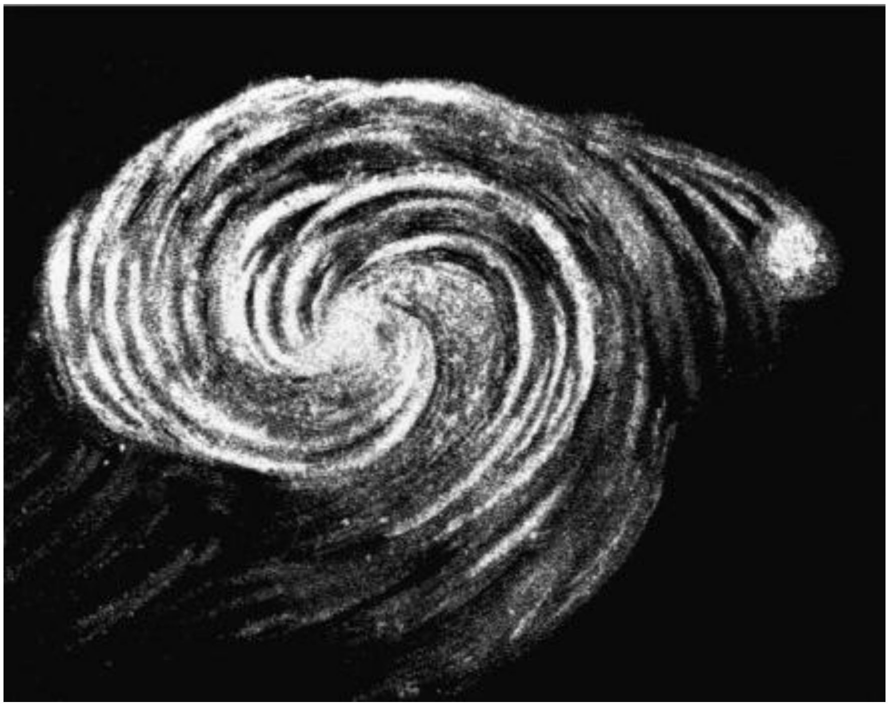


Figure 14

Spiral galaxy M51 and its companion galaxy NGC 5195. This was the first detected spiral nebula; Lord Rosse detected the spiral feature of this galaxy in 1845 and produced this drawing of it. This pictorial representation appeared in Neil F. Comins and William J. Kaufmann III, *Discovering The Universe*, (New York: W. H. Freeman and Company, 2008), p. 435.

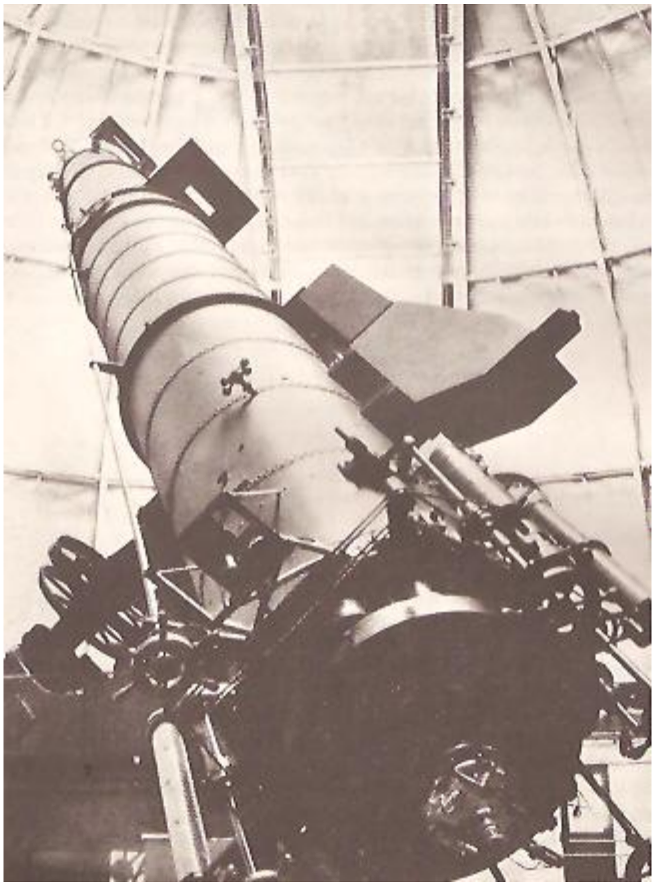


Figure 15

The 40-inch Yerkes telescope with nebular spectrograph. This photo appeared in Henry C. King, *The History of the Telescope*, (New York, NY: Dover Publications, Inc., 1955), p. 363.

Figure 16

The 60-inch Mount Wilson telescope that was completed in 1908. This photo appeared in Allan Sandage, *Centennial History of the Carnegie Institution of Washington: Volume 1, The Mount Wilson Observatory: Breaking the Code of Cosmic Evolution*, (Cambridge: Cambridge University Press, 2004, p. 168.

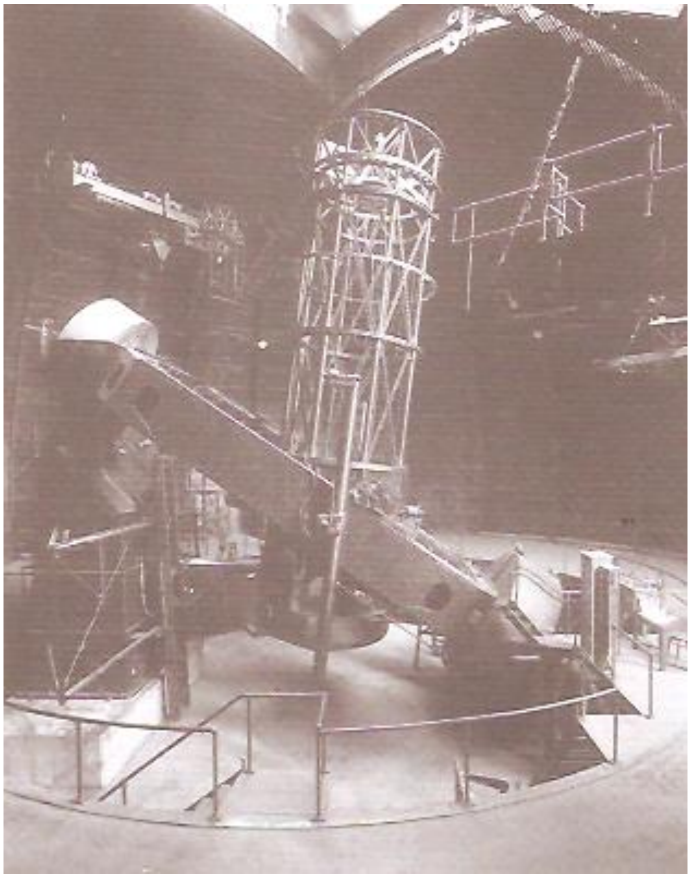


Figure 17

The 100-inch Mount Wilson telescope that was completed in 1920. This photo appeared in Allan Sandage, *Centennial History of the Carnegie Institution of Washington: Volume 1*, *The Mount Wilson Observatory: Breaking the Code of Cosmic Evolution*, (Cambridge: Cambridge University Press, 2004, p. 176.

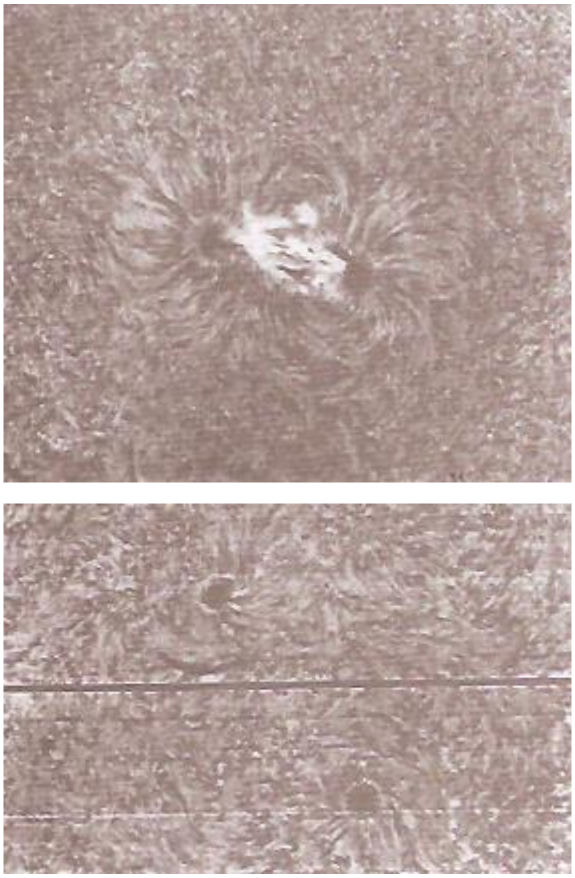


Figure 18

The top image shows solar vortices around a bipolar sunspot group; the bottom image shows the pattern around unipolar spots. Note the similarity between these images and the pattern of iron filings attracted to the poles of a magnet. This similarity suggested to Hale the existence of magnetic fields in the sun. This photo appeared in Allan Sandage, *Centennial History of the Carnegie Institution of Washington: Volume 1, The Mount Wilson Observatory: Breaking the Code of Cosmic Evolution*, (Cambridge: Cambridge University Press, 2004, p. 75.

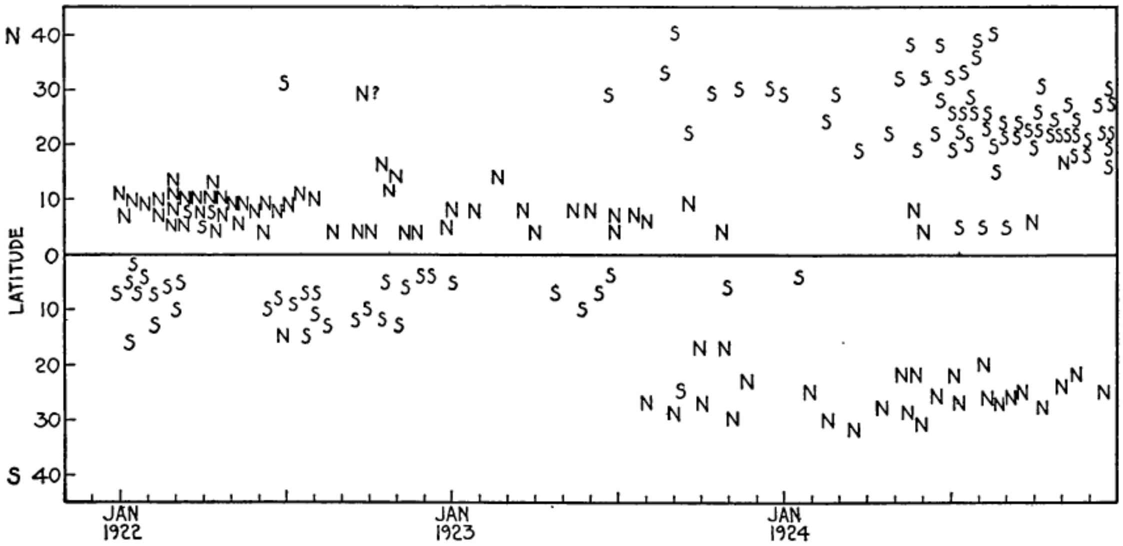


Figure 19

Hale compiled his data on sunspots polarity in this chart. “Heliocentric latitudes and magnetic polarities of sun-spot groups observed at Mount Wilson from January 1, 1922 to January 1, 1925. N (north-seeking) or S (south-seeking) represents the polarity of the preceding spot of each group. This chart appeared in George E. Hale and Seth B. Nicholson, “The Law of Sun-Spot Polarity”, *Astrophysical Journal,* vol. 62 (1925), p.270-300, especially p. 296.

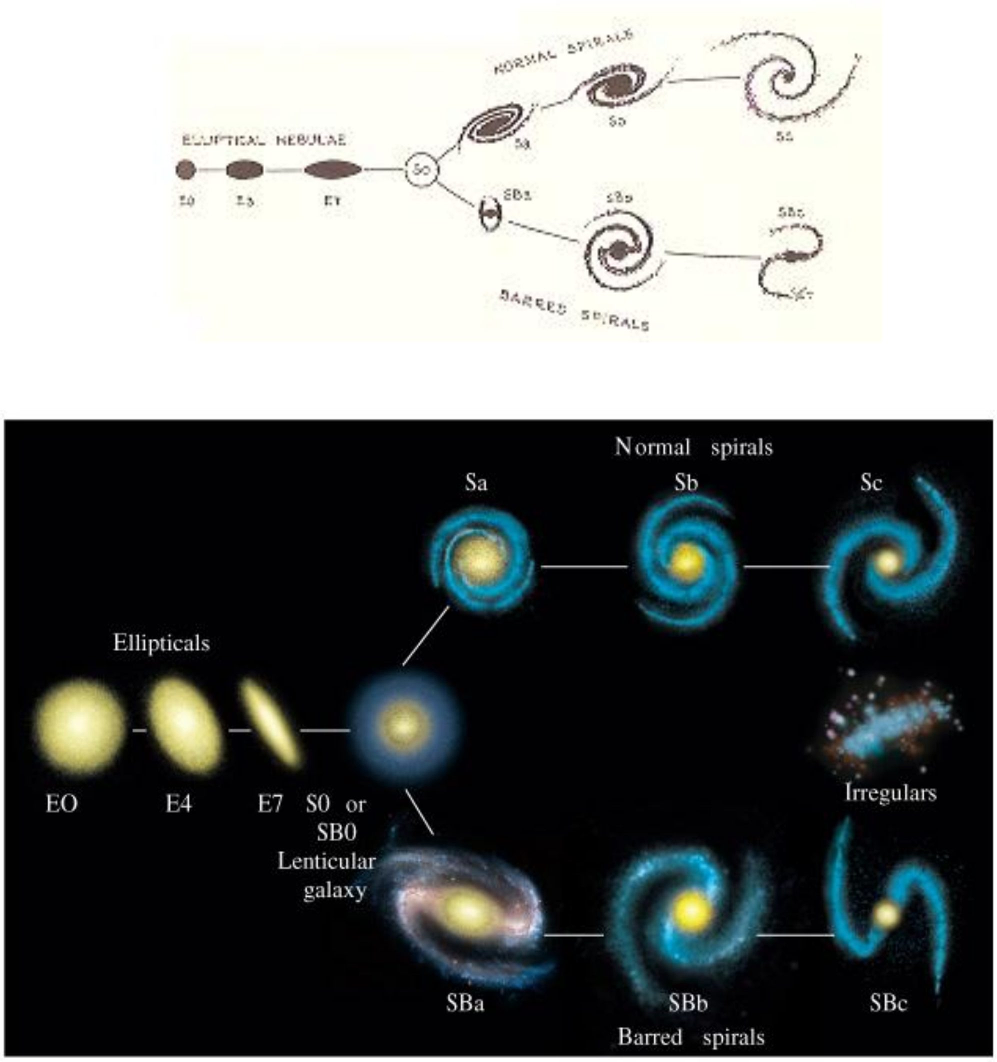
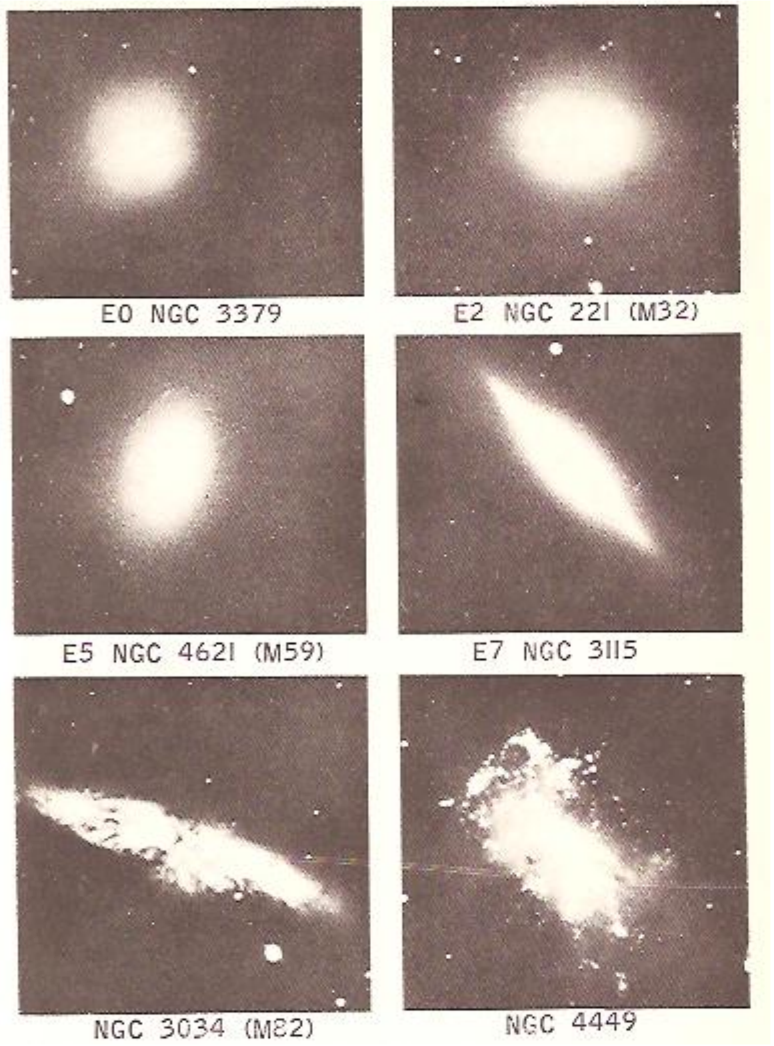


Figure 20

Top: Hubble's sequence of nebular type. This pictorial representation appeared in Edwin Hubble, *The Realm of the Nebulae*, (New York: Dover Publications Inc., 1958), p. 45. Bottom: Hubbles's nebular sequence became known as Hubble's classification scheme of galaxies which resembles a tuning form diagram. Elliptical galaxies are classified by how oval in shape they are; spiral and barred spiral galaxies are classified by how tightly wound they are and how big their central bulge is. This diagram appeared in Neil F. Comins and William J. Kaufmann III, *Discovering The Universe*, (New York: W. H. Freeman and Company, 2008), p. 460.



E0 NGC 3379
E2 NGC 221 (M32)
E5 NGC 4621 (M59)
E7 NGC 3115
NGC 3034 (M82)
NGC 4449

Figure 21

Types of elliptical and irregular nebulae. In Hubble's classification, an E0 elliptical nebula is round; the E7 is an elliptical nebula more oval in shape than E0. The bottom two images are irregular nebulae. These photos appeared in Edwin Hubble, *The Realm of the Nebulae,* (New York: Dover Publications Inc., 1958), Plate I.

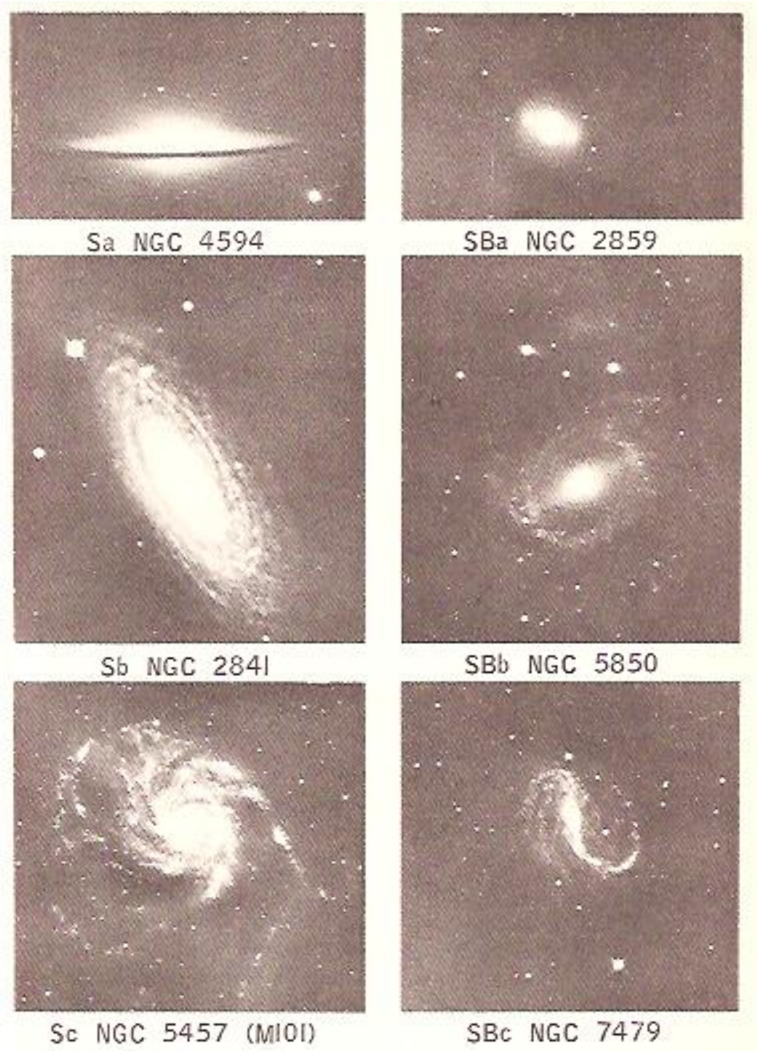


Figure 22

Types of spiral and barred spiral nebulae. In Hubble's classification, Sa and SBa spiral and barred spiral nebulae have a larger central bulge then S and SBc. These photos appeared in Edwin Hubble, *The Realm of the Nebulae*, (New York: Dover Publications Inc., 1958), Plate II.

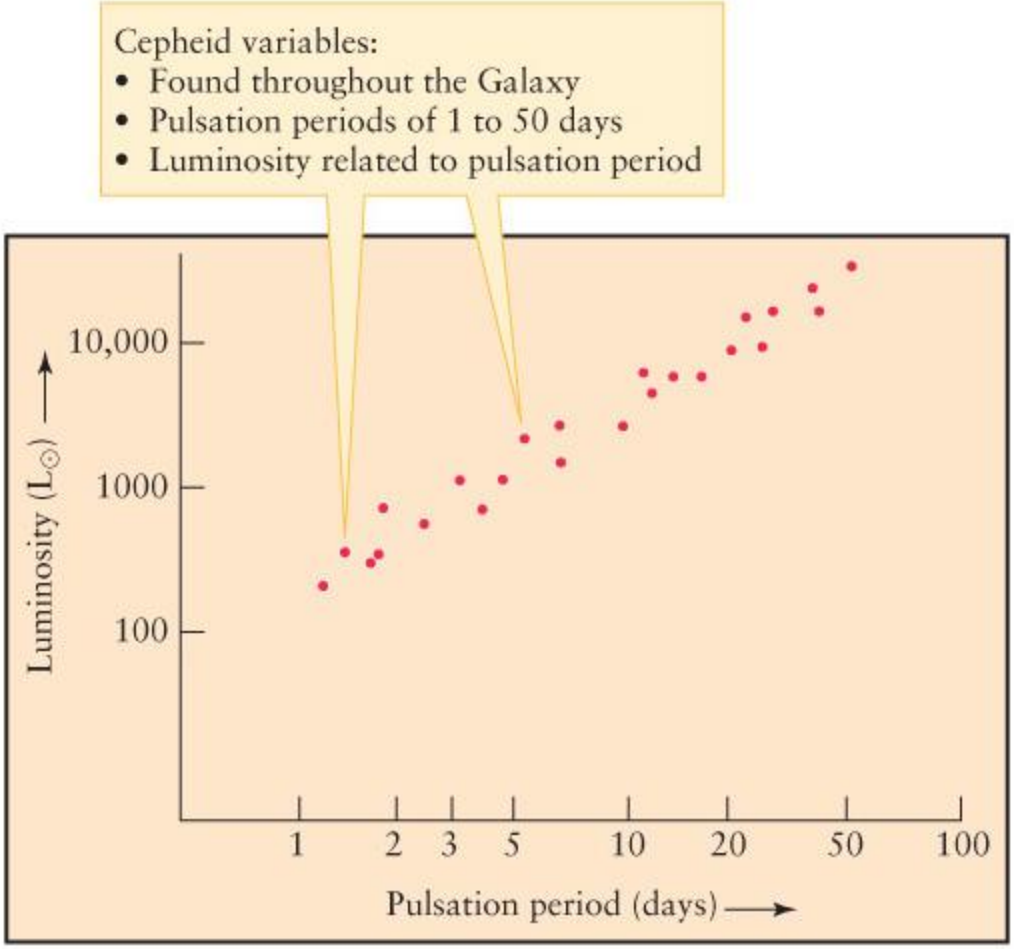


Figure 23

The period-luminosity relation graph shows the linear relationship between the period of pulsation and the luminosity of Type I Cepheid variable stars; each dot re[resents a Cepheid star.. This is adapted from a graph that appeared in Neil F. Comins and William J. Kaufmann III, *Discovering The Universe*, (New York: W. H. Freeman and Company, 2008), p. 436.

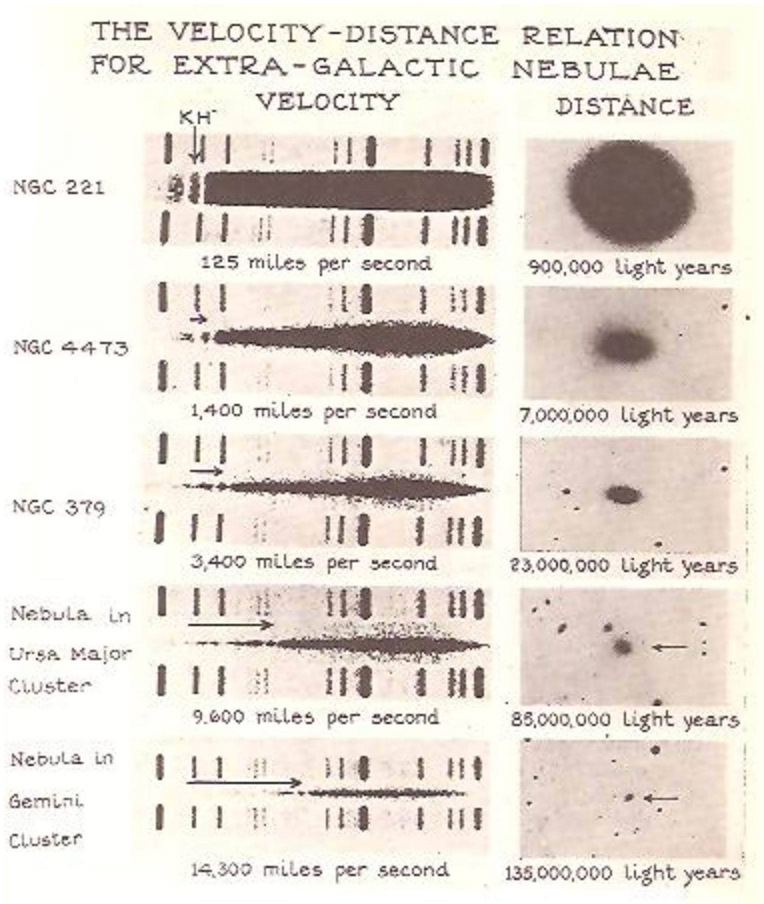


Figure 24

Images of five elliptical galaxies (taken at the same magnification) and their corresponding spectral lines. The Doppler shifts are indicated with the arrow below each spectrum. Note that the fainter galaxy (which would be more distant) has a greater redshift indicating that it is moving away from us faster. These photos appeared in Edwin Hubble, *The Realm of the Nebulae*, (New York: Dover Publications Inc., 1958), Plate VIII.

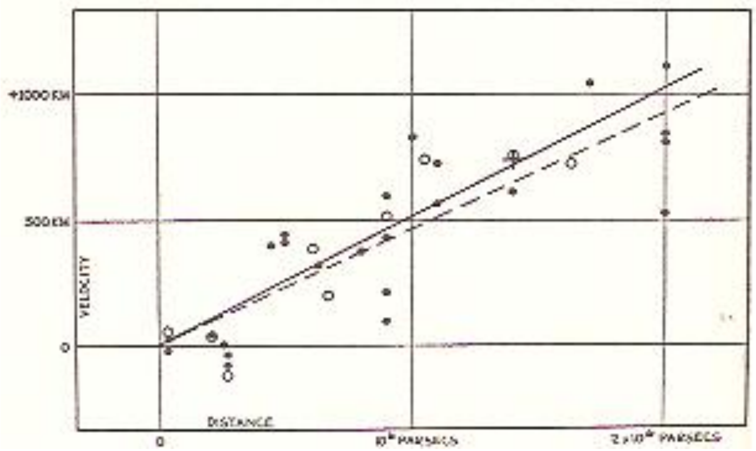


Figure 25

Hubble’s formulation of the velocity-distance relation between observed nebulae and their measured distances. The vertical axis represents the velocity of observed nebulae in km/sec and the horizontal axis represents their distance in parsecs. Hubbles used this relationship in conjunction with the larger redshifts of more distant galaxies to formulate his theory of our expanding universe. This graph appeared in Edwin Hubble, *The Realm of the Nebulae,* (New York: Dover Publications Inc., 1958), Plate VIII.