2-2015

Technological Revolution in Astronomy

Michael Julio

Graduate Center, City University of New York

How does access to this work benefit you? Let us know!

Follow this and additional works at: https://academicworks.cuny.edu/gc_etds

Part of the History of Science, Technology, and Medicine Commons

Recommended Citation

https://academicworks.cuny.edu/gc_etds/579

This Thesis is brought to you by CUNY Academic Works. It has been accepted for inclusion in All Dissertations, Theses, and Capstone Projects by an authorized administrator of CUNY Academic Works. For more information, please contact deposit@gc.cuny.edu.
This manuscript has been read and accepted for the Graduate Faculty in Liberal Studies in satisfaction of the requirement for the degree of Master of Arts.

Thesis Adviser: ___________________________ Date: __________________
Joseph W. Dauben

Executive Officer: ___________________________ Date: __________________
Matthew K. Gold

THE CITY UNIVERSITY OF NEW YORK
Abstract

TECHNOLOGICAL REVOLUTION IN ASTRONOMY

By

Michael Julio

Adviser: Professor Joseph W. Dauben

This thesis examines the evolution of technology in astronomy and how it has impacted our understanding of the universe. It also gives a brief history of the major figures that revolutionized the science through their innovations and discoveries. Technological advancements throughout the last four centuries have allowed for the construction of instruments that can be used to see further into the universe than ever before. Thanks to technology, astronomers can now look beyond the electromagnetic spectrum as the only means of studying the compositions of celestial objects, opening a whole new way in which we can study the universe. We are at an age in which we can stop hypothesizing about the nature of the universe and begin to understand it like never before.
I would like to thank Professor Joseph W. Dauben, who guided me throughout this project. This thesis would not have been completed without his constructive criticism and advice.
## Table of Contents

Introduction........................................................................................................................................... 1

Part I: A Brief History of Astronomy before Galileo ............................................................................. 2
  1.1 Pre-Telescope Astronomy .................................................................................................................. 2
  1.2 The Naked Eye .................................................................................................................................. 9
  1.3 The Telescope .................................................................................................................................. 11

Part II: From the Refractor to the Reflector ............................................................................................. 15
  2.1 Galileo Galilei .................................................................................................................................. 15
  2.2 The Refracting Telescope after Galileo .............................................................................................. 19
  2.3 The Reflecting Telescope .................................................................................................................. 22

Part III: Astronomy in Great Britain ........................................................................................................ 27
  3.1 The Royal Greenwich Observatory ................................................................................................... 27
  3.2 William Herschel .............................................................................................................................. 28
  3.3 Thomas Cooke and the Introduction of Factory Methods ................................................................. 32
  3.4 The Decline of British Science ......................................................................................................... 33

Part IV: Astronomy in the United States .................................................................................................... 34
  4.1 The Beginnings of Astronomy in America ......................................................................................... 34
  4.2 American Observatories and the Pioneers of American Astronomy ............................................... 35
  4.3 The Birth of Astrophysics ................................................................................................................ 42

Part V: The Astronomical Revolution of the Twentieth Century ............................................................... 48
  5.1 Exploring New Wavelengths ............................................................................................................. 48
    5.1.1 Radio Astronomy ......................................................................................................................... 49
    5.1.2 X-ray Astronomy ......................................................................................................................... 51
    5.1.3 Infrared Astronomy .................................................................................................................... 53
  5.2 Observations beyond the electromagnetic spectrum .......................................................................... 56
    5.2.1 Cosmic Rays ............................................................................................................................... 56
    5.2.2 Neutrino Astronomy .................................................................................................................. 57
    5.2.3 Gravitational Waves .................................................................................................................. 59
List of Illustrations

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The Pythagorean system</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Classical Greek geocentric and heliocentric systems</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>The Ptolemaic planetary model</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>Thomas Harriot’s Moon drawings</td>
<td>13</td>
</tr>
<tr>
<td>5</td>
<td>The Galilean Telescope</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>Optical aberration</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>Galileo’s drawings of the Moon</td>
<td>17</td>
</tr>
<tr>
<td>8</td>
<td>The Keplerian Telescope</td>
<td>20</td>
</tr>
<tr>
<td>9</td>
<td>Hyperbolic lens</td>
<td>22</td>
</tr>
<tr>
<td>10</td>
<td>The Mersenne Reflector</td>
<td>23</td>
</tr>
<tr>
<td>11</td>
<td>Gregory’s Reflector</td>
<td>24</td>
</tr>
<tr>
<td>12</td>
<td>The Newtonian Reflector</td>
<td>25</td>
</tr>
<tr>
<td>13</td>
<td>The Cassegrain Reflector</td>
<td>26</td>
</tr>
<tr>
<td>14</td>
<td>Herschel’s 40-foot telescope</td>
<td>30</td>
</tr>
<tr>
<td>15</td>
<td>Solar spectrum</td>
<td>45</td>
</tr>
<tr>
<td>16</td>
<td>Hydrogen-alpha spectroheliogram</td>
<td>47</td>
</tr>
<tr>
<td>17</td>
<td>The electromagnetic spectrum</td>
<td>48</td>
</tr>
<tr>
<td>18</td>
<td>Radio Telescope</td>
<td>50</td>
</tr>
<tr>
<td>19</td>
<td>X-ray Telescope</td>
<td>52</td>
</tr>
<tr>
<td>20</td>
<td>Infrared constellation</td>
<td>55</td>
</tr>
<tr>
<td>21</td>
<td>Iconic images taken by the Hubble Space Telescope</td>
<td>64</td>
</tr>
</tbody>
</table>
Introduction

The study of the universe is a fascinating subject, but if it had not been for the last four hundred years of technological innovations we would not understand it to the extent that we do today. The instruments used by astronomers have drastically changed over the centuries since the introduction of the telescope in 1610, and as a result, our perception of the universe has changed as well. Technology has always been a critical component of what is considered to be the oldest science, but it was not until the introduction of the telescope during the Scientific Revolution that we truly began to see the impact technology has had in astronomy. Technology has allowed humans to build tools that can gather more light than what the naked eye is capable of processing, allowing for the study of astronomical objects not visible to the unaided eye. The four centuries that have followed since the invention of the telescope have witnessed technological innovations that have allowed for great scientific discoveries. Another dramatic leap forward in the science of astronomy came during the twentieth century, with the introduction of the computer chip, which allowed astronomers to collect even larger, in fact vast quantities of data. Technology has allowed humans to stop hypothesizing about the cosmos based on simple observations, and has enabled us to finally begin to understand how the universe works. Scientists now have tools at their disposal that allow them to peer deeper into space than ever before, but with every discovery made, new questions arise.
Part I: A Brief History of Astronomy before Galileo

1.1 Pre-Telescope Astronomy

The history of astronomy is an extremely broad and complex subject. Virtually every early civilization gazed up at the sky in order to tell time, to aid in agriculture, to serve for navigational purposes, or to determine the timing of religious observances. In the 1970s the American archaeologist Alexander Marshack examined a 30,000 year old Paleolithic bone found in Drodogne, France, on which he found marks that he identified as showing lunar phases. Stonehenge, built in three phases between 3000 BC and 1600 BC, allowed the Druids to mark the solstices [Kuhn 1957: 11]. The temple of Karnak in Egypt, built by ancient Pharaohs to honor the god of the Sun, Amun Ra, was constructed to align with the winter solstice. Along with the Egyptians, the Babylonians, Mayans, and Incas, among many others, also devised tools to aid in their observations of the sky [Kuhn 1957: 9]. However, it is the astronomy of the ancient Greeks, as passed on by the Arabs, which is considered to be the source of modern astronomy.

In the sixth century BC, Pythagoras and his followers, the Pythagoreans, applied mathematics to the study of the cosmos, which they believed to be the result of harmonious relationships. In the Fifth century BC, Philolaus, a Pythagorean, developed a cosmological system in which the celestial bodies revolved around a central fire. The center was considered the most important part of the system and because of this, the Earth could not occupy that position, since fire was believed to be a more honorable element than earth [Huffman 2006: 244]. This system contained ten bodies, the central fire, counter-Earth, Earth, Moon, Sun, Mercury, Venus, Mars, Jupiter, and Saturn, all of which revolved around the central fire which could not be seen from Earth. Philolaus also introduced the counter-Earth, which was a hypothetical celestial body rendered the central fire invisible because of its location, always
between the Earth and the central fire. Aristotle argued that Philolaus introduced the counter-Earth in order to explain lunar eclipses, since it was presumed that the Moon did not receive its light from the Sun but from the central fire. He also suggests that the counter-Earth was conceived to have the heavenly bodies equal ten in total, which the Pythagoreans believed to be the perfect number [Burch 1954: 257–258]. The Pythagoreans viewed numbers as patterns of dots which formed different geometrical shapes. The number ten, which is the result of adding the numbers one, two, three, and four, was represented by a triangular shape known as a *tetraktys* [Koestler 1959: 30].

![The image on the left shows the Pythagorean system with the Earth, Counter-Earth (CE), and the Sun. The image on the right shows the *tetraktys*.

**Figure 1.** The image on the left shows the Pythagorean system with the Earth, Counter-Earth (CE), and the Sun [Stanford Encyclopedia of Philosophy n.d.]. The image on the right shows the *tetraktys*.

Around the third century BC, Aristarchus postulated that the Earth may rotate on its axis on a daily basis while revolving annually around the Sun, but his proposition was rejected in favor of a system in which the Earth was stationary at the center of the cosmos. The basis for the cosmological system that would come to dominate astronomy for nearly two thousand years was that of the “Concentric Spheres.” Originally proposed by Eudoxus of Cnidus in his work titled *On Speeds*, and later elaborated on by Callippus and Aristotle, this system consists of celestial
spheres made of ether.\textsuperscript{1} Classical Greeks believed that circular motions were sufficient to explain planetary motion [Clagett 1955: 87]. Thus ancient Greeks explained the movements of heavenly bodies by developing a system which consisted of sophisticated networks of spheres. The Sun, Moon, planets, and the fixed stars were presumably embedded within rotating spheres, the axis of each sphere was fixed on another sphere, the outermost of which was called the \textit{Primum Mobile} [Hall 1962: 40]. Spheres were chosen not only because the heavens appear to be spherical, but also because the shape was presumed to be the most perfect form. Aristotle argued that the sphere was a complete shape, since it is composed of a single surface, and like the circle among the plane figures, the solid sphere is bounded by only one surface. He believed that the “shape of the heavens is on necessity spherical; for that is the shape most appropriate to its substance” [Aristotle \textit{De Caelo}, Book II, part 4 286b].

\textbf{Figure 2.} The image on the left shows the classical geocentric model of the Greeks. In this model the Sun, Moon, and planets rotate around the Earth. The image to the right shows Aristarchus’ heliocentric system, in which the planets, including the Earth, rotate around the Sun [Koestler 1959: 48].

\textsuperscript{1} Ether is the classical element that was assumed to comprise the spheres of the heavenly bodies, and unlike the other elements, it was not subject to change. Aristotle believed that ether was neither heavy nor light, and that it moved naturally with uniform circular motions [Grant 1996: 64].
Although the actual reasons why ancient Greeks rejected a heliocentric systems are unknown, a number of explanations have been given in order to explain their preference for geocentricism. A Sun-centered system could have been rejected because of the lack of any visible stellar parallax during night time. Aristarchus was able to explain this by arguing that the stars were much further away than most believed them to be. The distant position of the stars in relation to the Earth, he argued, resulted in an undetectable displacement in their position [Clagett 1955: 91]. Another explanation, as philologist William Harris Stahl argues, was that Aristarchus’ theory was conceived in a period when observations and practical applications were preferred over theories [Stahl 1945: 329]. For example, the prominent astronomer Hipparchus was well-known for his careful astronomical observations based on an Earth-centered cosmos. Most of what we know of Hipparchus comes from Ptolemy’s *Almagest*, a treatise highly influenced by Hipparchus.

One of the major flaws of a strictly geocentric system was that it did not explain the inequality of the seasons, since in a system of perfect spheres, where the Sun rotates around the Earth at a constant speed, the seasons should be of equal length. Hipparchus accounted for this by removing the Earth from the center of the Sun’s orbit. His observations of the equinoxes and solstices drove him to the conclusion that the Earth was not at the exact center of the Sun’s orbit, but slightly off-center. He determined that the ratio of eccentricity of that orbit was 1:24, and concluded that the time period between the spring equinox and summer solstice was 94 ½ days, whereas the period between the summer solstice and the autumn equinox lasted 92 ½ days [Jones 1991: 102]. The ancient Greeks were able to explain the inequality of the seasons, as well as the

---

2 Stellar Parallax is the apparent change in the position of a star as seen from two separate points. This change is too small to be detectable with the naked eye.
Sun’s apparent motion through the sky, with the geocentric model, but were unable to completely understand the irregular motions and varying speeds of the planets.

The term “planet” comes from the Greek verb, “to wander,” a name given to the planets because of their apparent back and forth movement through the night sky. During a planet’s regular eastward motion, it suddenly stops and for a period of a few months, depending on the planet, then begins to move westward before returning to its eastward path. This reverse movement is called retrograde motion. We now know that this happens when the Earth passes the superior planets during its orbit around the Sun, while the inferior planets exhibit an apparent retrograde motion when they pass between the Sun and the Earth during their orbits. In order to account for the retrograde motions of the planets, ancient Greek astronomers, including Hipparchus, modified the cosmological system of the concentric spheres by introducing the deferent and epicycle [see figure 3]. During the second century AD, Claudius Ptolemy further modified the geocentric system in order to account for the variations in the planets’ speeds.

Ptolemy greatly admired the work that had been done by the likes of Hipparchus and Aristotle, so much so that for his own theories he “drew freely from the observational data and geometrical ideas of Hipparchus to which he added his own” [King 1955: 7]. In his Syntaxis Mathematica, later known as the Almagest—the title of which comes from combining the Arabic Al “the” and the Greek magiste “greatest”—Ptolemy, like Hipparchus before him, argued that the planets moved along on small circles called epicycles, which moved along longer circles called deferents, and together these movements caused a planet to move closer to them and further from the Earth at different points in its orbit, thereby causing their irregular paths. According to French scholar Pierre Duhem, Ptolemy’s theories, and those of the Greeks before him, were devised in order to “save the phenomena.” Duhem argued that ancient astronomers’ hypotheses
were not meant to explain accurately how the cosmos worked, but to provide theories that would explain what they observed [Goldstein 1997: 2].

Ptolemy placed the Earth in an eccentric model where it was not at the exact center of its sphere, but off center. The middle of the sphere was a point between the Earth and the equant, a mathematical concept developed by Ptolemy to explain the varying speed of a planet [see figure 3]. Ptolemy developed the equant to allow for more accurate observations of planetary motion. The equant replaced the notion that planets moved in perfect concentric circles, and also added an increased complexity to the system of concentric spheres. However, the equant is particularly important to the history of astronomy because it served as the one feature of Ptolemaic cosmology that Copernicus rejected [Kuhn 1957: 71].

One of the major problems with the traditional system of epicycles developed by the ancient Greeks was that it produced retrograde loops of equal size throughout a planet’s path through the sky. This was a problem since this system could not explain the large difference between the retrograde loops of Mars. Ptolemy introduced the equant in Almagest IX, but does not give any information on how he developed the concept, however, most historians believe that was to better explain the irregular retrograde arcs of Mars [Evans 1984: 1088]. The equant was a point located directly opposite the Earth, and the planet’s deferent circle was assumed to move at a uniform speed around the equant, but because of its off-centered location, the planets’ speed appeared to be faster or slower when observed from Earth [Hall 1962: 45]. Also, by having the center of a planet’s orbit at a distance from the Earth, Ptolemy was able to produce retrograde loops that were more consistent with those that the planets appeared to follow through the sky. Despite the fact that Ptolemy’s equant violated the traditional belief that the cosmos operated
under uniform circular motion, the Ptolemaic system would become the chief astronomical system until the introduction of the Copernican heliocentric system in the sixteenth century.

Figure 3. The Ptolemaic planetary model (left), wherein the small circle represents the epicycle while the larger circle is the planet’s deferent. The center of the planet’s orbit lies between the Earth and the equant (Q) [Bothun n.d.]. The image on the right shows how this system accounted for retrograde motion by illustrating the planet’s path [Sagan 1980].

Nicolaus Copernicus (1473–1543) is often regarded as the man who sparked the Scientific Revolution, which would forever change the history of mankind. In 1543 he published *De revolutionibus orbium coelestium*, wherein he postulated the theory of a Sun-centered cosmos. This influenced a generation of brilliant men who challenged the traditional Aristotelian cosmology while seeking to learn the true nature of the cosmos. According to I. Bernard Cohen, Copernicus was not a revolutionary, but rather a conservative astronomer, and the fact that he was “unable to go beyond the basic principles of Aristotelian physics hampered him” [Cohen 1985: 25]. The Polish astronomer has also been described as the last great practitioner of ancient astronomy, which is evident in the fact that *De revolutionibus* follows Ptolemy’s *Almagest* in its structure [Thoren, in Taton and Wilson 1989: 3].

Copernicus sought to find a way in which he could best describe the motion of the planets, Sun, and Moon, while still following the Aristotelian notion of perfect spheres. But did
not agree with Ptolemy’s introduction of the equant, since it violated the principle of uniform circular motion by introducing angular motion to planetary movement by which the planets no longer moved in perfect circles with uniform speeds. In 1514, the Lateran Council asked Copernicus to advise Pope Leo X on the reformation of the calendar, however, Copernicus declined because he believed that calendar reform should be postponed since the current cosmological system then in use did not allow for proper calculation of an accurate calendar. Renaissance astronomers were not the first to realize that the Julian calendar did not accurately reflect the tropical and solar year, but it was Copernicus that argued that an astronomical reform was needed as well [Kuhn 1957: 126]. While attempting to redefine the system of celestial spheres, Copernicus realized that by placing the Sun in a fixed position near the center of the cosmos, with the planets moving around the Sun, he could more naturally and easily explain the apparent motions of the planets. Copernicus died the year *De revolutionibus* was published, and despite its controversial subject, it was well received and was later used by the Church to aid in the calendar reform [Hall 1962: 74].

1.2 The Naked Eye

Before the first known astronomical observations using the telescope in 1609, the naked eye was the most important tool used for studying the sky, but observations were limited by the eye’s low angular resolution, the inability to distinguish fine details between two objects even at relatively short distances from each other, or diseases that affected vision. Galileo likely had unilateral myopia uveitis, or creeping angle closure glaucoma, and lost his vision at the age of 72, whereas Kepler suffered from myopia and anocular polyopy for most of his life, which limited his ability to conduct astronomical observations [Koestler 1959: 139]. Such limitations associated with observing the night sky with the naked eye led astronomers to begin developing
instruments to aid them in their observations. Former director of Ohio Wesleyan University’s Perkins Observatory in Delaware, Nicholas T. Bobrovnikoff, has argued that the history of astronomy may be seen as a “struggle to overcome the limitations of our natural vision. The telescope was a premier step in that direction” [Bobrovnikoff 1984: 1]. The introduction of the telescope to astronomy over four hundred years ago completely revolutionized the science, but for thousands of years before that, the naked eye had been the primary instrument used for revealing the secrets of the cosmos.

For millennia astronomers had been restricted by what they were capable of observing by making use of their human senses. Under perfect night conditions, where the sky is free from any source of light pollution, the measurable brightness of a star, its apparent magnitude (m) that can be detected by the human eye is on the order of 6m, and it may be able to see stars as faint as 8m. Brighter stars have lower magnitude values. Since the night skies being observed by our ancestors were of optimal observing conditions, they were able to observe about 3,000 stars of 6m [Bobrovnikoff 1984: 3]. The human eye is also limited by the wavelength of the electromagnetic spectrum it can detect. The average person can detect wavelengths from about 390 to 700 nanometers (nm) of the electromagnetic spectrum, which corresponds to violet through red light. The angular resolution of the eye under these perfect conditions is approximately 1 archminute. The eye’s optimal resolution is obtained during photopic vision, well-lit conditions, while scotopic vision, low light conditions, is approximately seven times less [Bobrovnikoff 1984: 3]. Scotopic vision is produced at wavelengths of about 498 nm of the electromagnetic spectrum and at luminance levels of $10^{-2}$ to $10^{-6}$ candela per square meter.³ Our capacity to view only limited wavelengths of the electromagnetic spectrum also explains why the

³ Candela is the unit of measurement for luminous intensity of a light source in a particular direction.
night sky appears to be dark. Because the universe is expanding, distant stars are constantly moving away from us. The further away they are the redder they become due to the Doppler Effect, and they continue to become redder as they further distance themselves from our position until they eventually become infrared. Once this happens they are no longer visible to the naked eye. The importance of stellar colors did not begin to play an important role in astronomy until observational astrophysics emerged in the late nineteenth century.

1.3 The Telescope

The telescope was the first technological instrument to redefine completely the science of astronomy because of its ability to collect more light than the human eye is capable of processing. Therefore, the telescope can detect smaller objects and make them appear brighter. Telescopes work by using a convex and concave lens to focus light, making an object appear larger in size. The size of its larger lens, called the objective lens, determines how much light the telescope is able to collect. Although Galileo never claimed to be the inventor of the telescope, he is often given that honor by historians. Who was the actual inventor? This is a question that is still debated by historians. Galileo heard of the telescope while in Venice, where he heard that a Dutchman had invented a spyglass capable of enlarging an image by three times its actual size. The telescope that Galileo had heard about was probably the invention of Hans Lippershey from Middelburg, but historians have found that there may have been other telescopes before Lippershey’s invention in 1608 [King 1955: 30].

In 1589, the Italian natural philosopher Giambattista Della Porta published his Magia Naturalis in which he writes: “by means of a concave glass you will see distant objects small but

---

4 The term “telescope” was not introduced until the year 1611, when it was conceived by the Greek mathematician Giovanni Demisiani during a banquet at the Accademia dei Lincei in Rome, at which Galileo was present [King 1955: 38].
clear; with a convex glass, near objects magnified but dim. If you know how to combine them exactly you will see both distant and near objects larger than they would otherwise appear and very distinct” [Della Porta, as quoted in King 1955: 30]. Another man claiming to have invented the telescope was Zacharias Jansen, from Middelburg, Netherlands. Zacharias’ son, Hans Jansen, claimed that his father invented the telescope in 1590 and used it to observe the Moon and stars [King 1955: 32]. Despite who may have been the actual inventor, it was Galileo Galilei (1564–1642) who perfected its design, was among the first to use it to study the heavens, and was certainly the first to publish his results.

Although the first observations of a celestial object through a telescope are generally associated with Galileo, it was in fact the English astronomer Thomas Harriot who first depicted an astronomical object based on telescopic observations. Around 1609 Herriot obtained a Dutch telescope, and on July 26 of that same year, he pointed his spyglass to the Moon and produced the first illustrations of its surface [Casanovas 1997: 6]. Harriot’s drawings of the Moon were not nearly as detailed as the ones made by Galileo, since his telescope was not as powerful, but they did depict craters and the main lunar maria. Harriot’s observations were not published, which also explains why his work has been overshadowed by the work of Galileo. Between 1610 and 1612, Harriot made observations not only of the Moon, but also of Jupiter’s satellites and numerous observations of sunspots.
Figure 4. Moon map drawings by Thomas Harriot based on his observations of the Moon during 1609 and 1610 [The Galileo Project n.d.].

Galileo’s telescope, like those before his, was a refractor, comprised of lenses that he ground himself, which allowed him to improve the magnification capabilities of his spyglass. In only a matter of a few months after first hearing of the telescope, Galileo had managed to build one that was capable of magnifying an object by a factor of twenty. A cardboard stop was added to the objective lens in order to reduce the blurriness of the image without compromising the field of view, the visible area as seen through the telescope. Thanks to this, he was able to see, and document, the sky in a way that no one had been able to before.

Figure 5. The Galilean Telescope: $f_1$ represents the focal length of the objective lens, while the focal length of the eyepiece is shown by $f_2$. Light enters the convex objective glass where it is redirected to the eye by the secondary concave lens [American Institute of Physics n.d.].

The invention of the refracting telescope was an important moment in the history of astronomy; however, those who made use of it soon realized that the images observed were
distorted. Refracting telescopes produce distortions in the image as plano-convex and equi-
bianconvex lenses fail to focus all colors on the focal point, the area where rays of light converge,
resulting in what is known as chromatic aberration. This optical defect happens because the
reflective index of the lens varies with wavelength, so red rays are not bent as much as violet
rays, which have shorter focal lengths. Another optical distortion encountered by early users of
refracting telescopes was spherical aberration. Professor of Ophthalmic Optics at the
Northampton Polytechnic, London, H.C. King, explains:

When the object is both white and brilliant, like the planet Venus near maximum
elongation, the image cannot be focused sharply, and is marred by an encircling
halo of an intense blue. The disk of the moon under these conditions is likewise
surrounded by a colored blur, as are also the bright objects on it, all to the
detriment of definition [King 1955: 44].

This type of aberration happens because the curved surface of the lens blurs the image as light
from the edge of the lens focuses nearer the lens than does light at the center of the lens. A
number of natural philosophers sought to fix the problem of optical aberration throughout the
centuries following the introduction of the telescope. As we will later see in more detail in Part II
or this paper, Kepler theorized that the use of hyperbolic lenses would reduce aberration, while
Isaac Newton made use of mirror lenses rather than glass to fix the problem.

Figure 6. The illustration on the left shows the different convergence points of light that cause chromatic aberration,
while the illustration on the right shows those that cause spherical aberration [King 1955].
Part II: From the Refractor to the Reflector

2.1 Galileo Galilei

Why did Galileo chose to point his telescope to the heavens? The historian of science William Shea argues that it was to “confirm a conjecture that he had made in a satirical book published under the pseudonym of Alimberto Mauri in 1606. The changes in the features of the lunar surface that can be seen with the naked eye had been adduced as evidence that these are mountains on the moon” [Shea, in Machamer 1998: 214]. As mentioned previously, Galileo first heard of the telescope in July of 1610 while in Venice at the University of Padua where he was seeking to increase his salary, which he believed to be insufficient. The account of how he first heard of the telescope is documented in the Sidereus Nuncius:

About ten months ago a report reached my ears that a certain Fleming had constructed a spyglass by means of which visible objects, though very distant from the eye of the observer, were distinctly seen as if nearby… a few days later the report was confirmed to me in a letter from a noble Frenchman at Paris, Jacques Badouere which caused me to apply myself whole heartedly to inquire into the means by which I might arrive at the invention of a similar object. This I did shortly afterwards, my basis being the theory of refraction. First I prepared a tube of lead, at the ends of which I fitted two glass lenses, both plane on one side while on the other side one was spherically convex and the other concave [Galileo 1610/1957: 29].

Galileo returned to Venice on August 21, 1609, with a telescope of eight times magnification and showed it to the Venetian senators. Impressed by what they saw through the telescope, the senators increased Galileo’s salary from 520 to 1,000 florins. However, by this time the Dutch telescope had already spread throughout Europe, and when news of this reached the Venetian senators, they decided to put Galileo’s salary increase on hold until the end of his current contract [Swerdlow, in Machamer 1998: 244]. Galileo continued to perfect his telescope, building one capable of magnifying an object thirty times its original size, and when he pointed this telescope towards the Moon, he noticed that “its diameter appears almost thirty times larger. Its
surface nearly nine hundred times, and its volume twenty-seven thousand times as large as when viewed with the naked eye” [Galileo 1610/1957: 28]. Galileo’s ingenuity allowed him to create an instrument that he would use to make the discoveries that would mark the beginning of a new era of astronomy.

The year 1610 saw the publication of Sidereus Nuncius, a treatise published by Galileo that contains the first published telescopic observations of the heavens.⁵ One of the most astonishing discoveries documented in the short treatise was Galileo’s description of the surface of the Moon which, contrary to the beliefs of Aristotelian scholars, was not a perfectly smooth sphere. Instead, he found, that it was not much different than the rough, uneven surface of the Earth. He described the surface of the Moon which faces the Earth as he observed it:

For greater clarity I distinguish two parts of this surface, a lighter and a darker; the lighter part seems to surround and to pervade the whole hemisphere, while the darker part discolors the moon’s surface like a kind of cloud, and makes it appear covered with spots. Now those spots which are fairly dark and rather large are plain to everyone and have been seen throughout the ages; these I shall call the “large” or “ancient” spots, distinguishing them from others that are smaller in size but so numerous as to occur all over the lunar surface, and especially the lighter part. The latter sports had never been seen by anyone before me. From observations of these spots repeated many times I have been led to the opinion and conviction that the surface of the moon is not smooth, uniform, and precisely spherical as a great number of philosophers believe it (and the other heavenly bodies) to be, but is uneven, rough, and full of cavities and prominences, being not unlike the face of the earth, relieved by chains of mountains and deep valleys. The things I have seen by which I was enabled to draw this conclusion are as follows. On the fourth or fifth day after new moon, when the moon is seen with brilliant horns, the boundary which divides the dark part from the light does not extend uniformly in an oval line as would happen on a perfectly spherical solid, but traces out an uneven, rough, and very wavy line [Galileo 1610/1957: 32].

---

⁵ Sidereus Nuncius is often translated into English as Sidereal Messenger, although Sidereal Message and Starry Messenger are also acceptable translations. Historian of science, Stillman Drake, explains that after receiving criticism from a Jesuit for presenting himself as “messenger” of the stars, Galileo announced that while nuncius can mean both “message” and “messenger,” his intended meaning was the former [Drake 1957: 19].
Along with describing its rough surface, Galileo also explained that the secondary illumination of the dark portion of the Moon was caused by light reflected from the Earth rather than from light emanating from the Moon itself.

![Image of the Moon with illumination explained](image)

**Figure 7.** Galileo’s drawings of the Moon published in *Sidereus Nuncius* [The Galileo Project n.d.]

Among the discoveries also described in the *Sidereus Nuncius* were the Medicean stars, which Galileo named after Grand Duke Cosimo II of Tuscany. When Galileo pointed his telescope towards the planets Jupiter and Saturn he saw that they were not alone. On January 7, 1610, he observed that Jupiter was accompanied by three small stars to its side. The following night, two of these stars had moved from east of Jupiter to west of the planet, and six days later he saw a fourth star appear. Galileo realized that they were orbiting the giant planet, and named them Medicean stars, after the Grand Duke of Tuscany. This was an important discovery since it proved that Earth was not the sole, unique center of all planetary movements.

In July of that same year he pointed his telescope towards Saturn and saw what appeared to be two small stars east and west of the planet. It was unknown to Galileo what these “stars” could have been, and they would remain a mystery until 1659, when Christiaan Huygens

---

6 What Galileo observed were the four largest satellites of Jupiter. The term “satellite” (to guard) was not introduced until Johannes Kepler used the term in his *Narratio de Observatis a se quattuor louis satellitibus erroribus* (Narration About Four Satellites of Jupiter Observed) in 1610, so for Galileo “stars” was an appropriate term to describe what he observed [Swerdlow, in Machamer 1998: 253].
discovered that Saturn was surrounded by a flat ring. All of Galileo’s observations during 1610 were of great importance in demonstrating that Aristotle’s ideas of the cosmos were incorrect, since it showed that the heavens were not perfect.

Towards the end of 1610, after the publication of Sidereus Nuncius, through his observations of the planet Venus, Galileo discovered that the planet exhibits phases, and that it does not shine through light of its own, which meant that it must revolve around the Sun. Ptolemy had postulated that Venus was located between the Earth and the Sun, always appearing in front of it, but if this were the case the planet could never appear fully illuminated but would always appear as fully dark or as no more than a crescent in the sky. However, if it moved around the Sun, it would exhibit all of the phases as Galileo discovered and documented in Letters on Sunspots, published in 1613. This disproved the Ptolemaic order of that the heavens, and showed that at least Copernicus was partly right—Venus and Mercury must orbit the Sun.

In the year 1607, Johannes Kepler (1571–1630) unknowingly observed sunspots while attempting to study a transit of Mercury, which happens when the planet crosses between the Sun and the Earth and appears as a dark dot moving across the Sun. By using a device that projects an image onto a screen, called a camera obscura, Kepler tracked what he believed to be the transit of Mercury across the Sun [Casanovas 1997: 5]. Galileo began studying sunspots in 1610 and made of brief mention of them in the preface to Discourse on Bodies in Water (1612). Further observations convinced him that these spots were actually on the body of the Sun. In 1611 Christopher Scheiner (1573–1650), a Jesuit professor of mathematics in Ingolstadt, Germany, wrote a number of letters to Marcus Welser, a German businessman and politician, about his observations of Sunspots and his theory about them. Although Welser was not an astronomer, his interest in the science led him to develop friendships with many astronomers throughout Europe.
Scheiner believed the spots to be small planets moving around the Sun, the best explanation that an Aristotelian scholar such as Scheiner could devise without disturbing Aristotelian theories about the perfection of the cosmos [Hall 1962: 325]. Welser sent the letters to Galileo, asking for his opinion. Galileo responded in a series of letters in which he refuted Scheiner’s theory by arguing that the spots originated on the solar disk and moved across its body in an irregular manner, so they could not be planets. After the publication of *Letters on Sunspots*, Kepler wrote in his 1617 *Ephemerides*: “lucky me, the first in this century to see a sunspot!” [Gingerich, in Taton and Wilson 1989: 70].

Galileo’s telescope and discoveries were of great importance in laying the foundations for a new understanding of the cosmos, different from what the Greeks and Arabs had imagined. Galileo proved that the heavenly objects were not perfect, nor was the imperfect Earth unique. His work with the telescope laid the foundation for modern observational astronomy, and would inspire a number of natural philosophers to follow in his footsteps and continue to perfect the telescope by minimizing its optical defects. The year 1610 may be regarded as the year that sparked a revolution in astronomy, one that would greatly impact the future of science in the Western world.

2.2 The Refracting Telescope after Galileo

The first improvement on the refracting telescope after Galileo came from Johannes Kepler, who for a time worked as an assistant to Danish astronomer Tycho Brahe, the most accomplished astronomer before the introduction of the telescope. Kepler was an important figure in the history of astronomy who formulated the three famous laws of planetary motion. Before obtaining his first telescope in 1610 from Ernest, Archbishop of Cologne, Kepler gave a brief description of the anatomy of the human eye in his *Supplements to Vitellio*, published in
1604. He learned about the anatomy of the eye from anatomist Johannes Jessenius, who had severed as Kepler’s sponsor at his first meeting with Tycho Brahe [Casper 1993: 166]. Kepler would later use this knowledge to write about the human eye in more detail in his *Dioptrice*, published in 1611. Kepler wrote on the anatomy of the eye as well as on his studies of refraction, and addressed the issue of spherical aberration, which he believed to be fixable by using hyperboloid lenses, a conclusion he arrived at from studying the eye, since it is free of this sort of aberration. Kepler believed that the back surface of the crystalline lens behind the iris, which allows for light to be focused on the retina, must be hyperbolic instead of spherical [Southall 1922: 832].

It was also in his *Dioptrice* that Kepler introduced his design for a refracting telescope capable of offering a larger field of view by replacing the eyepiece’s concave lens with a convex lens. Kepler’s telescope gave an inverted image, but its longer focal length allowed for considerable increased magnification. However, despite writing on how to improve the refracting telescope, there is no evidence to suggest that Kepler actually built one [Southall 1922: 836]. The idea of using an aspherical lens to focus all wavelengths at one point would later be revisited by French natural philosophers René Descartes and Marin Mersenne.

![Figure 8. The Keplerian Telescope: The focal length of the objective glass is shown by $f_1$. The focal length of the eyepiece is represented by $f_2$. This type of telescope had a high focal length in order to minimize aberrations [American Institute of Physics n.d.].](image)
The second half of the seventeenth century saw the introduction of telescopes many times longer than those available previously, since they allowed for greater magnification and a larger field of view. In the 1670s Johannes Hevelius of Danzig built a large Keplerian telescope with a focal length of 45-meters, which allowed for higher magnification and reduced aberration [King 1955: 50]. In 1659, Christiaan Huygens’ *Systema Saturnium* referred to a telescope much longer than the 45-meter telescope built by Hevelius. Four years earlier Huygens, along with his brother Constantine, built a telescope with a focal length of 123 feet. Using this telescope Huygens studied the planet Saturn, which he had already observed in 1655 when he discovered the bright satellite Titan, and after continued observations of the planet he discovered that what Galileo had believed were two small stars on each side were in fact thin, flat rings surrounding the planet.

H.C. King best describes Huygens’s telescope:

> He mounted the object-glass in a short, iron tube and placed it on a high pole. A groove running up the mast enabled the lens mount, counterpoised by a lead weight, to be either raised or lowered. The lens carrier was mounted on a ball-and-socket joint, operated from the ground by means of a connecting thread or string and reached, when necessary, by a series of triangular steps. The image produced by the lens was received by an eyepiece supported by two wooden feet and attached to the free end of the thread [King 1955: 54].

Huygens also developed an eyepiece which corrected chromatic aberration by placing two thin convex lenses separate from each other. Refracting telescopes had become important tools for astronomical observations, and by the end of the century they could be found in most observatories throughout Europe. However, chromatic and spherical aberration would continue to be a major problem.
2.3 The Reflecting Telescope

Isaac Newton (1642–1727) is often credited with the invention of the reflecting telescope. However, despite the fact that he was the first to correctly suggest that mirrors could be used to eliminate chromatic aberration, he was not the first to propose the use of mirrors rather than glass lenses on telescopes. About two decades after Galileo’s and Kepler’s work on the telescope, René Descartes (1596–1650) published his *Dioptrique*. Descartes approached the problem of optics geometrically, which led him to discover the law of refraction, which had been previously discovered by Willebrord Snel independently from Descartes. What Snell discovered was that the ratio of the sine of the angle of incidence and the sine of the angle of refraction is constant when light passes from one medium into another. Descartes’ work on the geometry of spherical lenses led him to the conclusion that a telescope’s aberration could be decreased, and magnification increased, by shaping the back curved surface of a plano-convex lens into a hyperboloid [King 1955: 48]. Descartes attempted to grind aspherical lenses by building his own grinding machines in the 1620s, but was unsuccessful in creating one that would polish an aspherical surface, which is very difficult to accomplish.

*Figure 9.* Image of a lens with a hyperbolic back. The light rays entering the lens come at a focus at one point (T) minimizing aberrations [Graham Burnett 2005].
In 1636 Marin Mersenne (1588–1648), a French theologian, mathematician, and music theorist, proposed using two concave paraboloidal mirrors rather than glass lenses. The idea was to replace the objective lens with a mirror which would reflect on a second mirror, allowing the image to be focused behind the objective mirror. However, Mersenne faced the same difficulties that Descartes had encountered when attempting to grind paraboloidal mirrors. The Frenchmen never attempted to build a reflecting telescope, since Descartes believed the idea to be a waste of time because of the difficulty of grinding the shape necessary for the mirrors [King 1955: 48].

![Figure 10. The Mersenne Reflector: The primary mirror is represented by (A), while (B) represents the secondary mirror which is mounted just beyond the focal point (F) [King 1955].](image)

In 1663 the Scottish mathematician James Gregory (1638–1675) introduced a new design for a reflecting telescope in his work titled *Optica Promota*. Gregory’s reflector consisted of a paraboloidal concave primary mirror which reflected light to a smaller elliptical secondary mirror which in turn reflected light to the observer. This configuration could significantly reduce chromatic and spherical aberration, but Gregory only met disappointment when trying to make his aspherical mirrors, since opticians at the time could not yet polish mirrors in the non-spherical shapes Gregory desired [King 1955: 71].
Optical aberrations continued to puzzle astronomers for the greater part of the century, until Isaac Newton solved the mystery by studying the properties of light. Newton suggested that what we perceive as white light is actually a combination of many colors, each of which had an independent characteristic index of refraction. Newton began his study of light in 1663, and by conducting prism experiments with light and color, concluded that dispersion is a result of refraction. Newton explains:

From what has been said it is also evident, that the Whiteness of the Sun's Light is compounded of all the Colours wherewith the several sorts of Rays whereof that Light consists, when by their several Refrangibilities they are separated from one another, do tinge Paper or any other white Body whereon they fall. For those Colours are unchangeable, and whenever all those Rays with those their Colours are mix'd again, they reproduce the same white Light as before [Newton 1718: 134].

Newton realized that it would be impossible to prevent the dispersive effect of curved lenses, and this led him to use a mirror as the objective lens of a telescope in order to prevent chromatic aberration. Although not the first to propose a telescope using concave mirrors, Newton was the first to build one, an achievement that would help him earn membership in the Royal Society.

The first successful reflecting telescope was built in 1668, and as I. Bernard Cohen writes: “Newton… showed astronomers how to transcend the limitations of telescopes built of lenses” [Cohen 1985:148]. Newton’s telescope worked by utilizing a small flat secondary mirror.
positioned at a 45 degree angle to the tube in which it was mounted, and this mirror reflected the convergent light to a focal plane at the side of the tube and into the eyepiece. Newton built his own grinding machine in order to grind the mirrors necessary for his telescope, and after experimenting with a number of different metals finally arrived at a custom composition of speculum metal which he used to grind a 33 millimeter mirror. One year after Newton finished working on his second reflecting telescope in 1671, a Frenchman by the name of Laurent Cassegrain (1629–1693) also built a reflecting telescope, but one heavily criticized by Newton.

**Figure 12.** The Newtonian Reflector (left). Light reaches the eyepiece (EF) after it is reflected by the primary mirror (CD) to the secondary mirror (AB) which is at a 45 degree angle to the axis of the tube [King 1955]. The image on the right show an illustration from Newton’s Notebook of 164 leaves (originally 166). Newton documented the process of shaping a wheel for lens grinding [Cambridge University Library nd.].

Cassegrain’s reflecting telescope was first mentioned in 1672 in the French journal, *Recueil des mémoires et conférences concernant les arts et les sciences*, where an account was given of Cassegrain’s invention. His version of the reflecting telescope used a hyperbolic secondary mirror to reflect light from a parabolic primary mirror back to a hole in the primary mirror. In 1672, Newton wrote to the Royal Society describing faults with Cassegrain’s design, and was highly critical of the Frenchman’s method, since “unless the secondary convex mirror had a true hyperboloidal figure, it would add to the aberrations of the large mirror and so make the instrument almost useless” [King 1955: 76]. Newton’s views went unchallenged, and

---

7 Metal speculum is the result of mixing approximately two-thirds copper with one-third tin, creating a brittle alloy that can be polished for use as a telescopic mirror.
Cassegrain was quickly forgotten due to the criticism received from such an important figure as Newton. However, Newton overlooked the possible advantages of Cassegrain’s telescope, such as longer focus in a shorter tube, resulting in increased magnification.

![Diagram of the Cassegrain Reflector](image)

**Figure 13.** The Cassegrain Reflector. This configuration is similar to Gregory’s design, however, the secondary mirror (B) is a convex hyperboloid rather than a convex ellipsoid. This design allowed for equal magnification in a shorter tube compared to Gregory’s telescope [King 1955].

The seventeenth century witnessed a revolution in the science of astronomy as natural philosophers began to look for alternatives to Aristotelian science, and the telescope became the main instrument in helping them do so. By the end of seventeenth century large refracting telescopes could be found throughout Europe, and reflecting telescopes were also beginning to appear. However, the eighteenth century would have to wait until William Herschel began to exploit the power of the reflecting telescope to see further developments in astronomical technologies and new discoveries.
Part III: Astronomy in Great Britain

3.1 The Royal Greenwich Observatory

Much of the astronomical data utilized by Isaac Newton in his *Principia* came from observations conducted at the Royal Greenwich Observatory near London. After completion of the observatory in 1676, King Charles II appointed John Flamsteed (1646–1719) as the first Astronomer Royal. The observatory itself was poorly equipped in comparison to other European observatories like the Paris Observatory, which housed a 34-foot telescope. The Greenwich Observatory’s equipment consisted of a sextant with a radius of 7 feet, a three-foot quadrant, and two telescopes, one of 7-feet and another of 15-feet focus. The main purpose of the observatory was to make observations relevant to navigation for the Royal Navy. Flamsteed built an impressive catalogue of stars in which he detailed their positions and characteristics with precise accuracy. He did so by constantly upgrading his instruments, since he believed that precise observations could only be done by making use of the latest technologies [Higton, in Willmoth 1997: 113].

The data gathered by Flamsteed were of great importance to Isaac Newton, because his observations were essential to the conclusions he drew in revising the *Principia*. However Flamsteed’s friendly and professional relationship with Newton quickly began to deteriorate as Newton grew tired of Flamsteed’s obsession with providing the most accurate data possible, since he needed Flamsteed observations of the Moon’s orbit in particular to continue work on his theories. Eventually Newton, along with Flamsteed’s rival Edmund Halley, seized the unfinished work and published it under the name of *Historia Coelestis*. As president of the Royal Society, Newton gave Halley control over the editing of the observatory’s observations and star catalogue [Willmoth 1997: 13]. Enraged, Flamsteed did all that he could to prevent the distribution of the
stolen material, to which Newton responded by removing all references to Flamsteed from later editions of his *Principia*. Following these events, Flamsteed would spend the rest of his life gathering more data for his catalogue of stars, the *Atlas Coelestis*. This work would not be published until after his death in 1719, and included the positions of close to 3000 stars as well as observations of Uranus, which he believed to be a star.

3.2 William Herschel

Born in Hanover, Germany, William Herschel (1738–1822) became interested in astronomy at an early age, but would later become a successful musician for much of his young adulthood. His childhood interest of astronomy, however, resurfaced in 1766 when he purchased a quadrant, books on astronomy, an objective glass and eye piece, and a Gregorian reflecting telescope. Soon he found himself building refractor telescopes as long as 30-feet. Herschel began building reflectors after he learned how to make speculum mirrors, his first being a 5 ½-foot telescope. He pointed his first reflectors towards the rings of Saturn, and what he observed further motivated him to improve his skills in mirror polishing. He learned that “crocus powder on grooved and rouged pitch with water as lubricant would give a good reflective surface” [Jones 1978: 39]. He did all of his work by hand and developed his own techniques, which he would practice for the greater part of the day in order to perfect. Herschel developed his own reflector design by placing the mirror slightly off axis and viewed the image from an eyepiece in the front of the telescope which reduced aberrations when working at certain apertures, the diameter of the objective lens. Herschel’s telescopes allowed the observer to view stars as circles with limited diffraction rather than the pointed stars produced by other telescopes. His experience with building telescopes brought him to the conclusion that the diameter of the objective was the main factor in determining the final range of penetration into space of a telescope, since larger
apertures allow for sharper and brighter images. Despite building large telescopes, Herschel preferred to make most of his observations using smaller telescopes, since they were easier to operate and reduced the amount of time needed to prepare for observations.

His best known telescope was a 7-foot reflector which consisted of a 6 ¼-inch mirror. The observations and discoveries made by Herschel with this telescope, which included the discovery of the planet Uranus, the first planet discovered with a telescope, greatly impressed the president of the Royal Society and patron of the natural sciences, Sir Joseph Banks, who brought Herschel to the attention of King George III. As a result, Herschel was summoned to Windsor by the King, and after demonstrating the capabilities of his telescopes, the King made him his private astronomer. Herschel was to receive a yearly salary of 200 pounds, which allowed him to give up his job as a musician and focus entirely on astronomy. Following the success of his 7-foot telescope, Herschel set out to build bigger, more powerful telescopes, the first being a 20-foot long reflector with a mirror that measured almost 19-inches. Herschel used this 20-foot reflector to do most of his work, along with the help of his sister Caroline, who recorded his observations. Although he preferred smaller telescopes, in 1785 he began to construct what would become the biggest telescope in the world [King 1955: 134].

With a 2000 pound grant he received from King George III, and an extra 2000 pounds after its completion, Herschel began building a 40-foot reflector with a 48-inch primary mirror. The casting of such a large mirror proved to be difficult. The first mirror did not end up as he had originally expected as it was too thin in the center, while a second mirror cracked while cooling. Herschel supervised a crew of 24 men in charge of polishing a third mirror, and despite its high copper content, which would cause the mirror to tarnish, thus was deemed suitable for use. Once
completed, the mirror was placed in a 40-foot long tube roughly 5-feet in diameter. As with his previous telescopes, the eyepiece was placed at the top.

Shortly after its completion in 1789, this telescope was used to discover two satellites of Saturn. Herschel also observed the Orion Nebula with his 40-foot telescope, and was able to distinguish small stars in the nebula. However, despite having a telescope which gathered four times as much light as his 20-foot reflector, Herschel continued to observe the skies with smaller reflectors since they were much easier to manage. The only usefulness he saw for such a large instrument was for observations of stars that other telescopes were incapable of reaching. Also, before the 40-foot reflector could be used for the night, the telescope’s lens needed to be uncovered before preparation could begin, while observations required the help of two assistants. Despite being the largest telescope in the world for fifty years, it did not prove to be much of an improvement over smaller telescopes due to its many issues. By 1815, after the mirror had become highly tarnished due to its high copper content, Herschel stopped using it [King 1955: 133].

![Figure 14. Herschel’s 40-foot telescope [Jones 1978].](image-url)
Along with his technological innovations, Herschel also greatly contributed to the science of astronomy with his discovery of infrared radiation. While attempting to study sunspots, Herschel placed filters of different colors behind the eyepiece of his telescope to protect his eyes, and he soon realized that the different colored filters reduced glare but did not prevent heat from getting through. He also found that the level of heat varied from color to color. Herschel experimented by measuring the temperature of each color of the solar spectrum by using a prism and three thermometers. He learned that the temperatures increased from the violet part of the spectrum to the red. While conducting these experiments, out of curiosity he also measured the temperature of the spectrum just beyond the red section and found it to be the highest of all, Herschel explained these experiments to the Royal Society in 1800:

In a variety of experiments I have occasionally made, relating to the method of viewing the sun, with large telescopes, to best advantage, I used various combinations of differently coloured darkening glasses. What appeared remarkable was, that when I use some of them, I felt a sensation of heat, though I had but little light; while others gave me much light, with scarce any sensation of heat. Now, as in these different combinations the sun’s image was also differently colored, it occurred to me, that the prismatic rays might have the power of heating bodies very unequally distributed among them; and, as I judged it right in that respect to entertain a doubt, it appeared equally proper to admit the same regard to light. If certain colors could be more apt to occasion heat, others might, on the contrary, be more fit for vision, by possessing a superior illuminating power [Herschel 1800: 255].

Herschel continued experimenting with rays found beyond the red portion of the spectrum and found that they acted in a similar manner to visible light. He thus discovered that not all light was visible, and the discovery of infrared light would become an important factor in the further evolution of astronomy.
3.3 Thomas Cooke and the Introduction of Factory Methods

Thomas Cooke (1807–1868) was born in Yorkshire, England. He was an optician and mathematician, owned a small optical business, and was the first British telescope builder to use factory methods for their construction. The first telescope Cooke built was a small reflector which would later encourage him to build bigger ones. His shop specialized in equatorially mounted reflectors. Cooke built a reputation for manufacturing quality instruments thanks to the 7-inch equatorial telescope he built for the Scottish Astronomer Royal, Charles Piazzi Smyth, and a 9 ½-inch equatorial he constructed for the meteorologist, John Fletcher Miller, of Whitehaven. In 1855 Cooke established the first telescope factory in England, and made use of machine tools he built himself along with other top-of-the-line machinery. Located in Bishops Hill, Yorkshire, the Buckingham Works factory initially began constructing telescopes of apertures which ranged from 5 to 10 inches. The success of his telescope factory was attributed to Cooke’s ability to obtain large optical glass sheets which he acquired from Britain’s leading glass manufacturing firm, Chance Brothers [King 1955: 252].

Cooke’s telescopes were widely sought throughout England. He gained a solid reputation thanks to his “careful design and execution of his medium-sized mountings and the high optical quality (by modern standards) of his objective-glasses” [King 1955: 252]. Cooke’s most ambitious project was the construction of the 25-inch Newall refractor in Gateshead, England, the largest in the world until the Royal Greenwich Observatory obtained a 26-inch refractor. Cooke began building the 25-inch telescope for wealthy amateur astronomer R.S. Newall in 1862. He obtained two large optical glass discs from the Chance Brothers firm, and floated them on Mercury before polishing to prevent them from curving too much. Cooke died in

---

8 Equatorial mounts are mounts that are designed to allow telescopes to follow the rotation of the night sky by having one axis aligned parallel to the axis of the Earth’s rotation.
1808, the year before the Newall telescope was completed. The telescope consisted of a 32-foot tube with a lens weighting 146 pounds and a focal length of 29 feet.

3.4 The Decline of British Science

Although England continued to be one of the leading scientific nations in the world, during the nineteenth century it began to lose its scientific supremacy to the United States. Throughout the 1800s American astronomy witnessed steady growth due to increased support from the public sector, as well as from government and educational institutions. English historian Margaret Gowing has argued that the decline of science in England was due to poor financial support for scientific and technical education from the government. Gowing also argues that because of England’s scientific achievements up to the early nineteenth century, the British did not feel the need to “create the educational infrastructure which her potential competitors were building in advance of their industrialisation” [Gowing 1978: 14].

In 1830 English mathematician, Charles Babbage, published Reflections on the Decline of Science in England: And on Some of its Causes, in which he attacked the state of science in England. Babbage criticized the government for its lack of support for science, the poor management of the Royal Society, and the disregard of science in universities [Weber 2000: 85]. In Reflections on the Decline of Science in England, Babbage argued for scientific reform by encouraging universities to include more science in their curriculums. Babbage also believed that membership into the Royal Society should be based solely on scientific merit, since many of the Society’s members, while prominent members of society, were not scientists [Weber 2000: 85]. While the British were fighting for scientific reforms, the United States’ scientific reputation was quickly growing throughout the world, particularly in astronomy, and by the end of the century, American astronomy was the foremost in the world.
4.1 The Beginnings of Astronomy in America

The first documented celestial observation by a European in the Americas was made by Thomas Harriot in 1585, as a member of an expedition team sent to colonize Virginia. Harriot observed a comet which he would document three years later in *A Briefe and True Rept of the New Found Land of Virginia*. For most of its early history, the astronomy of the American colonies was borrowed from England, with the Royal Society acting as its main patron. Many early Americans had an interest in studying mathematics, physics, and astronomy, since they were looking for ways to aid in the development of the colonies. Although most colonial scientists studied British science, men like Benjamin Franklin believed in the development of an American science, and in 1743 he founded the Philosophical Society [Holden 1897: 929]. The members of the Society sought to improve the conditions of agriculture, manufacturing, transportation, and to strengthen the economy of the colonies. In 1780 John Adams founded the American Academy of Arts and Sciences in Massachusetts, which along with the Philosophical Society, Harvard College, and Yale College, were the main scientific institutions for early American science.

The first telescope in the colonies was more than likely owned by John Winthrop, Jr., the son of the governor of Massachusetts [Yeomans 1977: 416]. In letters dating back to 1660, Winthrop writes about observing Saturn with his 10-foot telescope. However, in other letters addressed to the Secretary of the Royal Society, Henry Oldenburg, Winthrop explains that he encountered difficulties while trying to make objective and eyepiece lenses. The lack of adequate equipment would hamper most American scientists’ attempts to build proper instruments, so it is likely that Winthrop acquired the lenses for his 10-foot telescope from England [Yoemans 1977:
Senior research scientist at the National Aeronautics and Space Administration’s (NASA) Jet Propulsion Laboratory, Donald K. Yeomans, explains that while there was an interest in astronomy among colonial scientists, “colonists still occupied a position in the scientific backwater when compared with contemporary European scientists. To a large extent, the lack of rapid advancement was due to a lack of instruments, libraries, and scientific intercourse” [Yoemans 1977: 425].

4.2 American Observatories and the Pioneers of American Astronomy

During the nineteenth century the United States began building observatories throughout the country, after President John Quincy Adams told Congress in 1825 that he felt no pride in the fact that while Europe had over one hundred observatories, there was none throughout the entire American continent. The basic problem was simply a great reliance on European equipment, since there was a lack of quality American lens makers. Prior to the 1850s, David Rittenhouse was the only American astronomer capable of constructing his own equipment, but when working on the construction of a temporary observatory in Norriton, Pennsylvania, Rittenhouse imported most of his bigger instruments from England. The Hopkins Observatory at Williams College in Williamstown Massachusetts, which opened in 1838 and is generally considered the oldest observatory in the United States, followed by the Harvard College Observatory a year later, also had all of their instruments imported from Europe. While most of the equipment in the first American observatories was made in England, Americans began to develop the necessary skills to grind their own lenses during the nineteenth century. One of the first to do so was Alvan Clark (1804–1887).

Alvan Clark was originally a portrait painter. When he became interested in telescopes, he approached the director of the Harvard College Observatory, W.C. Bond, for an opportunity
to look at “The Great Refractor” telescope. Clark proceeded to learn and master lens making, which he did by working on old lenses. Soon he was making lenses which he considered to be of better quality than those made in Europe [King 1955: 255]. Clark’s reputation grew rapidly, especially after visiting London where he met many of England’s leading astronomers, and soon many astronomers throughout the world began to order his lenses. An 8-inch lens, which Clark manufactured for English astronomer William Rutter Dawes, was later given to William Huggins and placed in a telescope built by Thomas Cooke. This telescope would become the instrument most responsible for Huggins’ work in astronomical spectroscopy. In 1846 Clark founded the Alvan Clark & Sons Corporation, which would be responsible for making lenses for some of the largest telescopes in the world. In 1870 the United States government offered Clark $50,000 to build a telescope for the Naval Observatory in Washington, D.C. [King 1955: 257].

The Naval Observatory was the result of proposals that had been made as early as 1810 to build a national observatory. These proposals enjoyed the support of important figures such as Thomas Jefferson and John Quincy Adams, but most government officials were not willing to provide the funds for scientific research. It would not be until 1842 that Congress allowed for an observatory to be built after acknowledging the importance of astronomical observations in rating chronometers that were required for the creation of navigational charts on Navy vessels. Lieutenant James Gilliss was given the responsibility for planning the observatory and selecting the instruments. Gilliss imported instruments from England and Germany, and consulted prominent European astronomers in order to build what at the time was the best equipped observatory in the United States [Warner, in Gingerich 2010: 124]. The original observatory consisted of a 9.6-inch telescope made by the German optics firm of Merz & Mahler, which was later replaced in 1873 after a 26-inch refracting telescope was purchased from the American firm
of Alvan Clark & Sons. At the time, this was the largest in the world. However, being a branch of the Navy Department, the observatory’s main purpose was to serve the Navy by calibrating ship chronometers, which it did by timing the transit of stars across the meridian. All other scientific research was seen as a secondary function.

The scientific community viewed the Naval Observatory as a national observatory and often attempted to take control of it, creating tensions between civilian and naval scientists. A compromise was reached in 1894 when it was determined that the Naval Superintendent would remain the commanding officer, but responsibility for the “direction, scope, quality, quantity and publication of scientific work was given to the Chief Astronomical Assistant, a man chosen for his scientific rather than military credentials” [Plotkin, in Gingerich 2010: 127]. Because of the poor state of the building that housed the telescope, and also due to bad weather conditions, in 1893 the Naval Observatory was moved from the neighborhood of Foggy Bottom in North West, Washington D.C., to Massachusetts Avenue, where it remains to this day.

The first of the American observatories that would contribute significantly to the development of a new branch of astronomy, astrophysics, was the Harvard College Observatory, founded by William Cranch Bond (1789–1859) in 1839. However, the original location of the Harvard Observatory at a two story wood frame house known as “Dana House” was not fit to be used as an observatory, as it was not constructed for that purpose, and most of the instruments used during its first years came from Bond’s personal collection. In 1846 Harvard officials decided to move the observatory to a more suitable location, erecting a new building at Summerhouse hill on Garden Street in Massachusetts, and also arranged for the purchase of a 15-inch refractor from the German firm of Merz & Mahler. At the time of its completion “The Great

9 The Meridian is the line that passes through the poles and the zenith of a location.
Refractor,” as it was known, was the largest telescope in the United States until 1862 [Plotkin, in Gingerich 2010: 122].

W. C. Bond was made the first director of the new Harvard College Observatory in 1839, and along with his son, George Phillips Bond, he began observations of Saturn and Mars. Within a year, Bond discovered Saturn’s eighth moon, Hyperion [King 1955: 220]. The Bonds were the first to introduce the photographic technique known as daguerreotype to photograph astronomical objects, and were the first to take photographs of the Moon and stars. The observatory continued to grow as a prominent astronomical institution for the next three decades, but would see its biggest growth under Edward Charles Pickering (1846–1919), director from 1877 to 1919.

Because the observatory was operated as a separate department of Harvard College, it did not receive funds from the institution, rather it relied on endowments and publications. Pickering appealed to the public in order to secure funds for the continued operation of the observatory, and he personally donated over $100,000 over the years. In 1887 Boston lawyer, Robert Treat Paine, bequeathed approximately $300,000 to the observatory. In that same year Harvard received $238,000 from Boston engineer Uriah A. Boyden, to be used to build a high altitude observatory which would later be built in Arequipa, Peru. The widow of pioneer astrophotographer, Henry Draper, made The Henry Draper fund available to Pickering, which amounted to more than $385,000 between 1886 and 1914 [Plotkin, in Gingerich 2010: 124]. Not only was Pickering able to secure ample finances for the observatory, he also helped build Harvard’s research program by combining celestial photography with spectroscopy. This served to make the observatory an important institution in the development of astrophysics. Another
important and influential American who would help revolutionize astronomy was George Ellery Hale (1868–1938).

Hale became interested in astronomy at an early age, and as an adult developed a special interest in the physical properties of the Sun. He was among the firsts to argue that astronomy should not only focus on the location of a celestial object, but also on what it is made of. While still a university student, Hale’s interests led him to develop a telescope that allowed to photograph a single wavelength of the Sun’s light, known as a spectroheliograph, an invention that would become fundamental in the development of astrophysics. Hale was also largely responsible for the construction of a number of important observatories throughout the United States. He understood the importance of identifying the physical properties of astronomical objects, and because of this he believed that future observatories needed to be built around this concept.

The second half of the nineteenth century saw the construction of new, and bigger, observatories throughout the United States. Funds were made widely available, especially from those Americans who had “made their fortunes by methods which they, or the public, considered somewhat unethical; philanthropy allowed them to acquire social respectability and even immortality by giving them the means to have their names associated with a famous educational or scientific institution” [Brush 1979: 52]. One such philanthropist was streetcar and railroad tycoon Charles Tyson Yerkes. In the early 1890s, Hale was made aware by Alvan Clark that a 40-inch glass lens was available for purchase after the original buyer, the University of Southern California, could no longer pay for it. Hale approached and persuaded Yerkes to fund an observatory by telling him that his name would be attached to the best telescope in the world. Once completed, the Yerkes Observatory in Williams Bay, Wisconsin, was home to a 40-inch
refractor, as well as a laboratory designed for developing photographs and for conducting spectroscopic experiments.

Hale was also responsible for the construction of the Mount Wilson and Palomar Observatories, both located in California. In 1904 he was given $150,000 from Andrew Carnegie, and he used the money to build an observatory which housed a 60-inch reflecting telescope. While at Mount Wilson, Hale convinced businessman John D. Hooker to fund the purchase of a 100-inch telescope, completed at Mount Wilson in 1917. In 1928 Hale received $6 million from the Rockefeller Foundation, which he would use to construct the Palomar Observatory, but the observatory would not be completed until ten years after Hale’s death, in 1938 [Brush 1979: 54]. Thanks to investments in bigger telescopes, the United States was quickly rising to the top of the astronomical world.

Public interest in astronomy began to grow during the final decades of the nineteenth century, especially after Italian astronomer Giovanni Schiaparelli (1835–1910) made detailed observations of the surface of Mars in 1877, revealing numerous channels on the surface of the planet. Percival Lowell (1855–1916), a wealthy astronomer from New England, became interested in Schiaparelli’s examination of Mars and built his own observatory to further study the surface of the red planet. Lowell built his observatory in Flagstaff, Arizona, in 1894, in an area far away from any urban center. He understood that observatories needed to be located away from any centers that might generate too much light or locations which might hinder perfect atmospheric conditions [Brush 1979: 52]. Lowell was largely responsible for arousing public interest in astronomy in the United States. He also believed that there was another planet not yet found beyond Uranus and Neptune because of perturbations observed in the orbits of both
planets.\textsuperscript{10} In 1877 American astronomer Asaph Hall (1829–1907) used the Naval Observatory’s 26-inch refractor telescope to discover Mars’ two satellites, Phobos and Deimos. Astronomer James Keeler (1857–1900) discovered the gap in Saturn's rings with the Lick Observatory’s 36-inch Clark refractor, and also measured the radial velocity of nebulae using the Doppler Effect.

For the greater part of the eighteenth and nineteenth centuries, England and Germany were at the top of the astronomical world. Physicist and historian of science Stephen G. Brush argues that: “the French lost their high standing in physical science after the death of Laplace (1827) and never recovered it despite the isolated triumphs of Le Verrier and Poincaré in celestial mechanics” [Brush 1979: 45]. The Germans were the undisputed leaders in astronomy for most of the first half of the nineteenth century, while the peak of British astronomy came in the closing decades of the century.

It took less than a century for American astronomers to surpass the Germans and challenge the British for world supremacy in astronomy. By the end of the nineteenth century, European astronomers were traveling to the new observatories that were being built in the United States to conduct their research. Even before European scientists began migrating to the United States during World War II, astronomers often found themselves traveling to use American observatories, and upon returning to Europe they were frustrated by the inadequate and aging instruments available there [Brush 1979:48]. Growing economic support made the rise of American astronomy possible. Men like George Ellery Hale and E.C. Pickering were also greatly influential in the development of modern astronomy, not for their own astronomical

\textsuperscript{10} Lowell searched for “Planet X” until his death in 1916. On February 18, 1930, astronomer Clyde Tombaugh discovered a moving object photographed between January 23 and January 29, and after further study it was confirmed to be the planet for which Lowell had been searching. The discovery of Planet X, named Pluto, was announced on March 13, 1930. However, it is believed that the perturbations observed were simply a miscalculation as Pluto, now a dwarf planet, is not capable of altering the orbits of Uranus and Neptune [Brush 1979: 52].
discoveries, but for their ability to organize institutions that supported the purchase or construction of expensive equipment that was needed for new discoveries to be made.

4.3 The Birth of Astrophysics

For most of the nineteenth century the refracting telescope continued to be the main instrument in observatories throughout the world, since large reflectors required more money and greater skill to build. As interest in learning the physical properties of celestial objects grew, astronomers began to realize the limitations of refractors, mainly in the form of optical aberrations affecting photographic research. The need for telescopes that collected more light, thus providing more detail of the universe, would mark a revival of the reflecting telescope. As a result, the refractor was no longer seen as the premier observational tool, especially after mirror casting techniques and experiments with metal alloys began to improve towards the end of the century.

Telescope builders experimented with different alloys including platinum and silver, but while these materials allowed for a highly reflective surface they were not cost-efficient and tarnished quickly with time. However, in 1857 French physicist Leon Foucault (1819–1868) successfully treated glass optical surfaces with silver, since glass discs could be easily ground and figured. Foucault did this by using German chemist Justus von Liebig’s formula which consisted of nitrate of silver, with added caustic potash that acted as a sobering solution to which he added ammonia [King 1955: 262]. The resulting silver nitrate would release its silver when a sugar solution was added. This was then poured on the glass and the metallic silver would evenly spread on the surface. After a light polish, the resulting silver mirror would be less liable to tarnish. Foucault was able to build quality primary mirrors by using this method and grinding them to a good spherical shape. Parabolization is a crucial step in mirror making, as its purpose
is to produce a perfectly focused mirror in order to eliminate spherical aberration. Henry C. King explains how Foucault obtained the shape of his mirrors:

Parabolization was effected by abrading the center portion more than the outer with polishers of increasing size and using straight strokes across every diameter. For polishers he used plano-convex lenses of curvature slightly less than that of the mirror and covered with paper instead of pitch. The spherical surface was then carried through a series of ellipsoidal services to a paraboloidal one and, which was so important, was tested at each stage of the work [King 1955:264].

As silver glass mirrors were perfected, they quickly began to replace metal speculum mirrors as a main option for building reflecting telescopes. The introduction of astrophysics represented a major advance in astronomy, and the reflecting telescope was an essential instrument of this new branch of astronomy, which allowed scientists not only to determine where celestial bodies were located, but also of what they were composed.

The first astrophysics experiments can be traced back to Isaac Newton’s study of sunlight with a glass prism. However, the analysis of the spectrum of sunlight conducted by German optician Joseph von Fraunhofer (1787–1826) is more commonly considered the first actual research in astrophysics. Fraunhofer placed a prism in front of the objective lens of a telescope, and found missing lines of color in the spectrum of sunlight and bright stars which he was unable to explain. An answer would not be found until 1859, when German scientists Gustav Kirchhoff (1824–1887) and Robert Bunsen (1811–1899) discovered the cause of the Fraunhofer lines. The first step in identifying the lines observed by Fraunhofer was Bunsen’s invention of a gas burner which became fundamental in Kirchhoff’s method of producing spectra. He found that when a chemical element was heated using Bunsen’s burner it gave off its own set of colors and bright lines appeared. In most cases these lines appeared at the same point as Fraunhofer’s dark lines [King 1955: 283]. They discovered that every element had its own bright-line spectrum, which
indicated that the presence of a certain chemicals could be found in the Sun or a star. Studying spectra became a crucial part of astrophysics because it provided exact information about the chemical properties of a star.

For years after Kirchhoff’s discovery, careful examinations of the lines emitted by elements in their gaseous state were conducted. Meticulous observations were needed, since it was easy to confuse the numerous lines given by the spectrum, often in the high hundreds. Early astrophysicists dedicated themselves to classifying the stellar spectra. The two main methods of doing so were either by placing the prism in front of the telescope’s objective lens which resulted in lower dispersion of the spectra but greater brightness, or by using a device attached to the eyepiece of the telescope which contained one or more prisms between two complex lenses that produced a highly dispersed spectrum [Meadows, in Gingerich 1950: 12]. As interest in spectroscopy grew, more scientists began examining the solar spectrum, among them were William Huggins (1824–1910) in South London, England, and Angelo Secchi (1818–1878) at the Collegio Romano in Rome. While Secchi preferred to do his research by placing a prism in front of the telescope, Huggins used a spectroscope along with his 8-inch Clark refractor. Both men spent a considerable amount of time classifying stars based on their spectral characteristics. From their research three main categories emerged: blue and white stars with strong hydrogen spectral lines, yellow stars with strong metallic lines but weaker hydrogen lines, and red stars with heavy carbon lines. Along with the study of spectra, the introduction of photography to astronomy was also highly influential in the growth of astrophysics.
Figure 15. Diagram showing Fraunhofer’s solar spectrum. The stronger absorption lines are marked by capital letter from red to violet light [King 1955].

Although not widely accepted at first because of the long exposure time needed to capture light of astronomical objects, photography would become one of the main tools of astrophysicists. It was not until the final decades of the nineteenth century that professional astronomers began to see the usefulness of photographic plates for recording information found using telescopes, since it allowed for repeated study without having to prepare for a night of observing the same area on multiple occasions. The first scientist to successfully photograph the Moon was Anglo-American Chemist John William Draper (1811–1882). He accomplished this by using the early photographic process known as daguerreotype in which an image is produced on a silver plate fumed with iodine vapor and developed in mercury heated to 75 °C [Lankford, in Gingerich 1950: 16]. This technique was used until 1851, the year Frederick Scott Archer (1813–1857) introduced the wet collodion process. This consisted of a glass plate coated with a flammable solution of ether known as collodion, pyroxylin, and ether. The plates needed to be exposed while still wet, and once they dried were put into a solution that consisted of silver nitrate that converted the iodide into silver iodide. This process took considerable skill and was limited to exposures of 10 to 15 minutes, resulting in a much more sensitive process which was able to capture more light compared to the daguerreotype photographs, allowing for a more detailed picture of the night sky [Lankford, in Gingerich 2010: 17].
Lawyer and astronomer Lewis M. Rutherfurd (1816–1892) was also among the first American astronomers to employ the use of photography. He built an observatory in the garden of his New York home, where he made use of an 11 1/4-inch refractor telescope specifically designed for celestial photography. Using this telescope, Rutherfurd was able to take numerous photographs of astronomical objects including stars of up to an apparent magnitude of 9m [King 1955: 291]. Soon after this, Henry Draper (1837–1882) was able to successfully photograph the stellar spectra of Alpha Lyrae in 1872 with the use of a prism and his 28-inch reflector. Draper was also the first to introduce the silver-on-glass reflecting telescope to the United States, and was the first to use it for photographing the sky. He began constructing his own reflecting telescope by casting a 15-inch metal speculum, but while doing this he was made aware of the virtues of silver-on-glass mirrors used by Sir John Herschel [King 1955: 268]. Draper would continue to take photographs of astronomical objects, and took the first photograph of the Orion Nebula in 1880 using a 28-inch reflector telescope.

After Draper’s death in 1882 his wife, Anna Mary Palmer Draper, funded the establishment of a Department of Stellar Spectroscopy at Harvard College, and donated her husband’s 11-inch photographic telescope. E.C. Pickering, director of the Harvard Observatory, had already begun researching spectra and had begun an ambitious project of classifying the spectra of all stars in the northern hemisphere. The spectrographic survey began in 1885, and by 1889 Pickering and his crew of female astronomers, known as “Pickering’s Women,” had catalogued the photographic spectra of all stars in the hemisphere. By the beginning of the twentieth century, Pickering and his coworker Annie Jump Cannon organized stars based on their spectral lines in what became known as the Harvard Classification Scheme in which stars are classified using the following letters: O, B, A, F, G, K, and M. The scheme classifies stars
based on their surface temperature with O being the hottest, blue stars, and M being the coolest, red stars.

Although the introduction of photography to astronomy was a major step forward in the development of modern astronomy, however astrophysicists were limited by the tools at their disposal. The introduction of the wet plate was a major step forward in astrophotography, since it allowed for longer exposure times, but the spectrographs being used were also limited because they were low-resolution and often lacked optical quality. George Ellery Hale’s development of the spectroheliograph in 1889 allowed scientists to examine even more detailed features of the Sun, since the device gave an image of the entire star in a single wavelength of light, often hydrogen as it is the main chemical element present in the Sun. The image of the Sun enters the telescope through a narrow slit before passing through a spectroscope allowing for specific wavelengths to be photographed. This was a significant step forward in studying the composition of the Sun, since before the introduction of Hale’s spectroheliograph the Sun’s blinding glare made it difficult to photograph directly. The more advanced technologies introduced during the twentieth century would further revolutionize astronomy, and would help astronomers learn more about the universe than ever before.

Figure 16. Spectroheliogram taken at the Mount Wilson Observatory in California. The image above shows a full spectrum image of Hydrogen-alpha light [NASA History Program n.d.].
5.1 Exploring New Wavelengths

Visible wavelengths of light are only a small fraction of the radiation emitted by the cosmos. The universe is filled with wavelengths that cannot be seen with optical telescopes, but can be seen with other instruments that can peer even deeper into space. Prior to the twentieth century electromagnetic radiation from space could only be detected by astronomers in the optical portion of the spectrum, since the Earth’s atmosphere filters out many of the photons available in most regions, allowing only a very limited amount of radiation to make it to the ground to be detected by telescopes, thereby limiting our view of the universe. The only forms of electromagnetic radiation that can be detected from the ground are those from the visual, radio, and infrared regions. Once scientists discovered how to study other forms of radiation from the electromagnetic spectrum, astronomy once again witnessed a technological revolution that would allow the human race to understand the universe like never before, and this was only made possible by the availability of new technologies developed during the Second World War [McCray 2004: 154].

---

11 Electromagnetic radiation is made up of stream of photons traveling at the speed of light. Each photon carries a certain amount of energy. The different types of radiation these photons produce depends on how much energy they contain.
5.1.1 Radio Astronomy

Radio wavelengths were the first beyond the visible and infrared regions of the spectrum to be explored by astronomers during the twentieth century. This was made possible because of new technological developments that can be traced back to the 1930s when Karl Jansky (1905–1950), an employee of Bell Laboratories, was assigned to investigate the source of residual radio noise that could possibly interfere with transatlantic transmissions. Jansky built a rotating radio antenna that could detect frequencies of 20.5 megahertz (MHz), and discovered that static noise was coming from all directions. However, he was unable to find its source of origin and believed that it originated from radiation emitted by the Sun. Further investigation showed that the noise repeated every 23 hours and 56 minutes and came from the direction of the center of the Milky Way [King 1955: 436]. This discovery captured the attention of astronomers throughout the world, especially of amateur radio operator and astronomer, Grote Reber (1911–2002), who in 1943 built a radio telescope with a 31-foot diameter antenna which he used to conduct the first study of radio waves from space. Following the end of the Second World War, scientists were able to make use of surplus equipment that had been built for the war effort to continue investigations of radio waves emitted by celestial objects. The new radio technologies developed were especially useful in areas of the planet where optical observations were often hindered by poor weather conditions.

Radio telescopes differ from optical telescopes in that they are designed specifically to detect radio wavelengths, which are much longer and wider than visible wavelengths, resulting in weaker signals that can be detected from Earth. The telescopes used for radio astronomy consist of two main parts: the antenna and the receiver. A radio telescope’s antenna is the section of the instrument that is pointed in the direction the astronomer wishes to observe and collects
radiation which is then transferred to the radio receiver. The receiver then proceeds to process and record the signal, which can be done at different frequencies and bandwidths in order to achieve the best angular resolution. Because radio wavelengths are about one million times longer than visible waves radio telescopes have low angular resolution which makes forming images difficult [Smith 1995: 123].

The main feature of a radio telescope is the parabolic dish which focuses the radio waves onto a dipole antenna called the feed. These waves are then transmitted by the antenna to a central control room [Smith 1995: 107]. Ideally, equatorial mounts are used since they allow the telescope to follow a fixed point in the sky as the Earth rotates, but they are difficult and expensive to build. Because of this, only smaller radio telescopes are designed with an equatorial mount while the larger ones are mounted with an alt-azimuth configuration, and are controlled digitally by computers.12 The National Astronomy and Ionosphere Center in Arecibo, Puerto Rico, is home to the world’s largest single-dish radio telescope antenna measuring 300 meters [Cheng 2010: 158].

12 An alt-azimuth mount is a two axis mount designed to support and rotate an object, such as a telescope, perpendicularly.
Major advancements in the development of early radio astronomy were made at Cambridge University by the Cambridge radio astronomy group. Pioneer radio astronomer Martin Ryle, who would later receive a Nobel Prize for physics, created the first radio interferometer along with fellow radio astronomer D.D. Vonberg. Ryle understood that by placing a number of radio antennae hundreds of meters apart from each other the problem of low angular resolution from single dish antenna could be resolved [Longair 2004]. In 1964, members of the Cambridge radio astronomy group, Anthony Hewish and Jocelyn Bell Burnell in particular, began studying scintillation observed in radio sources emitted from solar winds. While conducting these studies they observed pulsating radio sources from what they identifies as rotating neutron stars, the team had discovered what we now know as pulsars.

5.1.2 X-ray Astronomy

X-ray astronomy had its start following the end of the Second World War thanks to the availability of technology that had been developed during the war. The first to experiment with x-ray astronomy was United States Naval researcher Herbert Friedman (1916–2000). In 1948, while experimenting with radiation detectors mounted on V-2 rockets, he found that the Sun emitted x-rays. Friedman continued his experiments for the next decade, but was unsuccessful in finding sources of x-ray emissions other than the Sun. In 1959 Italian astrophysicist Riccardo Giacconi and his group at American Science and Engineering Inc. (AS&E) while searching for x-ray emission from the Moon observed a high x-ray flux coming from the Scorpio constellation while searching for x-ray emission from the Moon, which they named Sco-X1. Giacconi writes: “Sco-X1 was an extraordinary object whose emission was 1000 times greater than that of the Sun at all wavelengths and 1000 times greater than its own optical emission” [Giacconi 2012:14]. The Sco-X1 discovery was achieved by launching a rocket with a payload of large detectors
specifically designed to detect x-ray photons, but these flights were limited to only a few minutes of observation time due to the rockets’ short flight time. Also, ground based observations are not possible since the atmosphere absorbs most x-ray radiation, so the only viable solution that allowed for long-term observations was by placing the detectors in space. The first major step forward in x-ray astronomy was the Uhuru satellite created by Giacconi’s team at AS&E and launched in 1970 [Smith 1995: 131]. Now, instead of only a few minutes of observation time, x-ray astronomers had a satellite which offered years of uninterrupted data. Thanks to the Uhuru satellite, the number of known x-ray sources increased from 30, which were found using V2 rockets, to close to 360 [Giacconi 2012: 16].

However, the main problem of x-ray observations is that due to the high energetic properties of photons, getting them to reflect in order to form an image is a difficult task, which makes imaging a very hard process. Because x-ray photons slam into the mirror of an optical telescope rather than reflect, the mirrors for these telescopes are shaped and aligned parallel to the paths of x-ray waves.

![Figure 19. X-ray Telescope: Illustration (b) shows the mirror configuration of an x-ray telescope. Illustration (a) shows the path of x-rays along the parallel mirrors before reaching the focal point [Nanjing University n.d.].](image)
NASA’s launch of the Einstein Observatory in 1978 marked a new era in x-ray astronomy. This space-based telescope was the first of its size to have mirrors, and the first to use x-ray imaging. Built by The Marshall Space Flight Center (MSFC) in Alabama, the Einstein Observatory was designed to be 100 times more sensitive than the Uhuru satellite and a million times more sensitive than the detectors mounted on rockets [Giacconi 2012: 17]. The Observatory contained two spectrometers and imaging detectors, and could achieve an angular resolution of 4 arcseconds.

In 1999 NASA launched the Chandra X-ray Observatory which was built by the same team that built the Einstein Observatory, and was 100 times more sensitive than its predecessor. The telescope included a mirror of 120-centimeters with a millionth-of-an-inch thick coat of iridium which absorbed x-ray photons more effectively. Images and spectral information were produced by ten charge-coupled device chips, digital image sensors, resulting in images 10 billion times greater than those produced in 1962 [Giacconi 2012: 26]. Chandra is considered one of NASA’s “Great Observatories,” which also includes the Hubble Space Telescope, the Compton Gamma Ray Observatory, and the Spitzer Space Telescope. The observatory’s discoveries since its launch in 1999 greatly advanced this branch of astronomy. Chandra was the first to detect x-ray emissions from the supermassive black hole at the center of our galaxy.

5.1.3 Infrared Astronomy

Other than optical and radio wavelengths, the only other region of the electromagnetic spectrum that can be detected from the surface of our planet is the infrared region. However, not all infrared radiation can make it to the ground, since the Earth’s atmosphere absorbs the longer wavelengths that lie closer to the microwave portion of the spectrum. The earliest studies of infrared radiation were done using the same techniques used by William Herschel in the
nineteenth century, which consisted of using thermometers to measure heat change. One of the main challenges of infrared observations encountered during the twentieth century is that a strong thermal background is always present [Smith 1995: 127]. Another obstacle to this branch of astronomy comes in the form of water vapor and carbon dioxide, since they absorb a large amount of infrared radiation. Because of this, telescopes that also conduct infrared observations must be located as high as possible [Smith 1995: 128]. Initially, infrared studies were conducted using balloons that were elevated to about 40 kilometers above the ground, but this was very limiting since the balloons could not carry a person.

Another way to study infrared radiation, developed during the 1960s and 1970s, is to place a telescope in an aircraft that could carry observers for hours at a time. In 1974 NASA created the Kuiper Airborne Observatory which consisted of a 36-inch reflecting telescope mounted inside a modified Lockheed C-141A Starlifter jet aircraft. The Kuiper Observatory was retired in 1995 and succeeded by the Stratospheric Observatory for Infrared Astronomy (SOFIA), which first flew on May 26, 2010. SOFIA was built using a modified Boeing 747sp and contained a 2.5-meter reflecting Cassegrain telescope. Its main objectives were to study planetary atmospheric composition, comet composition, and star formation. But even with the airborne observatories, thermal background noise remained an issue. A solution to this was the Infrared Astronomical Satellite (IRAS), the first space telescope to conduct infrared observations.

Launched in 1983, the IRAS was able to reduce background noise by a factor of $10^{12}$ [Smith 1995: 128]. This was made possible by cooling the telescope with liquid helium to minimize the number of particles generated inside the device, but this process also shortened the life of the telescope to only 10 months. Back on Earth, however, despite the fact that the planet’s
atmosphere absorbs most of the large wavelengths of infrared radiation, most modern optical observatories are also designed to detect infrared wavelengths, but in order to do so they had to be cooled with liquid nitrogen to reduce background noise. Although this process could reduce noise, it also produced condensation on the mirrors, a problem that did not affect the IRAS because of the vacuum of space [Smith 1995: 128]. During its 10 month mission, the IRAS scanned nearly the entire sky at a wide range of infrared wavelengths that are impossible to study from Earth. IRAS discovered disk of dust and gas around a number of stars, similar to that which surrounded the Sun during the formation of the planets in our solar system. This discovery showed astronomers that a large number of stars have planets orbiting around them [Henbest 1996: 89].

Infrared study is important for astronomy since it allows for the study of the early universe and the evolution of galaxies. Because the universe is expanding, and galaxies are moving further away, the light from the early universe has red shifted, this happens when wavelengths stretch and shift towards the red portion of the electromagnetic spectrum. Since much of the information the universe provides is in this invisible portion of the spectrum, infrared study has become a crucial component of modern astronomy.

Figure 20. Infrared image of the constellation Orion. The image on the left shows the constellation seen through the visible portion of the spectrum, while the image on the right shows the same area seen through the infrared portion, revealing gas and dust clouds forming new stars [WISE Berkeley 2010].
5.2 Observations beyond the electromagnetic spectrum

The twentieth century saw major advancements in all branches of astronomy, not only because scientists were able to tap into the information offered by the different regions of the electromagnetic spectrum, but also because it was discovered that studying electromagnetic radiation was not the only way to learn about the universe. Scientists have put a great effort into studying all possible sources of information that could help understand the nature of the universe.

5.2.1 Cosmic Rays

Cosmic rays are high energy particles consisting mainly of protons, electrons, and light nuclei, mostly originating outside of our Solar System, and were first detected in 1912 by Victor Hess using electrometers on a balloon at an altitude of 5 kilometers [Smith 1995: 137]. Hess found that ionization rates increased once the balloon rose above 1 or 2 kilometers. In the 1920s physicist Robert Millikan recognized that the high ionization rates observed by Hess were due to radiation that came from space and called them cosmic rays. Most of these rays are absorbed by the atmosphere but on rare occasions they can reach the surface of the Earth as electrons, those particles that reach the ground are known as secondary cosmic rays. The technologies developed to detect these high-energy particles range from ground based telescopes designed to detect particles such as photons, electrons, and protons, to detectors on satellites similar to those used to detect x-ray wavelengths. Particle physicists study cosmic rays as a cosmic source of photons and neutrinos which are useful in the search for theoretical particles [Gaisser 1990: 2]. Studying cosmic rays can also be very important to understanding our universe, since they originate beyond the solar system, and they can possibly contain significant information about our galaxy that is not available in the form of electromagnetic radiation. Supernova remnants have been the
only sources of cosmic rays observed so far, but detection of these particles is challenging since at such high energy, the flux of particles is small [Sommers & Westerhoff 2009: 4].

The study of cosmic rays is important because it is one of the few sources of matter from outside our solar system that can be studied from Earth. These particles contain important information about the chemical composition of our galaxy and allows astronomers to study how the galaxy has evolved. However, because cosmic rays are charged particles their course changes direction when interacting with magnetic fields, so detecting where they originated is difficult [Sommers & Westerhoff 2009: 3]. To find sources of cosmic rays, astronomers study photons rather than protons, since photons travel through space without interference from magnetic fields. When a high energy proton collides with another proton they create a pion, once the pion decays it created high energy photons that can be studied by scientist and reveal sources of cosmic rays.

5.2.2 Neutrino Astronomy

Neutrinos are particles with very little mass and no electric charge, and are created by nuclear reactions. They were first predicted in 1930 by Wolfgang Pauli as an attempt to explain the non-conservation of energy and momentum in radioactive decay [Smith 1995: 138]. He proposed a neutral particle that was responsible for carrying off the missing energy. Neutrinos were first observed by American physicist Clyde Cowan and Frederick Reines in 1956. These particles are extremely difficult to detect because they rarely interact with matter since they are almost completely massless.

The tools used to locate these particles are large instruments often built underground to avoid background radiation and cosmic rays from interfering in their detection. The detectors are often filled with heavy water which acts as the detecting medium. The Baikal Deep Underwater
Neutrino Telescope (BDUNT), located 1.1 kilometers under the surface of Lake Baikal, for example, is designed to detect neutrinos emitted by binary systems, faraway galaxies, and supernova remnants [Spiering 2000: 1]. Because these particles travel virtually undetected, scientists point the underwater telescope towards the bottom of the lake with hopes that the several kilometers of earth and water will act as a filter eliminating unwanted high energy particles that prevent neutrino signals from being detected.

Neutrino study is still in its infancy, so new technologies are still being developed. Scientists believe that neutrinos are abundant throughout the universe, so their study is of great importance to astronomers, since it is believed that because of their lack of interaction with matter, neutrinos that were created moments after the Big Bang could still be present today. Unlike cosmic rays, neutrinos are not affected by magnetic fields, this means that when detected their information has not changed. All the information that is known about stars has been gathered through the study of electromagnetic radiation that has traveled through the stars’ many layers, a process that takes millions of years. Neutrinos on the other hand, travel from the center of the star through its layers unchanged and in a matter of minutes. This is important since it can help understand the processes that happen inside stars.

Neutrinos were created in great numbers at the time of the Big Bang and continue to be created in stars throughout the universe, and there are an estimated 114 Neutrinos per cubic centimeter [Learned 1999]. Unfortunately, the only detected sources of neutrinos found to date are the Sun and the SN 1987A supernova detected by a Japanese deep mine detection facility eighteen hours prior to the first sighting of the 1987 supernova [Smith 1995: 141].
5.2.3 Gravitational Waves

Gravitational waves were predicted by Albert Einstein in 1915, based on his theory of general relativity. These waves are ripples caused by changing gravitational fields traveling outwards in space-time. Scientists believe that these waves travel throughout the universe at the speed of light, and that binary star systems could be a possible source of detectable waves [Smith 1995: 142]. In 2002 the National Science Foundation’s Laser Interferometer Gravitational-Wave Observatory (LIGO) in Hanford Site, Washington, began searching for gravitational waves by using laser interferometers. Eight years later the original detectors were disassembled and replaced with more sensitive detectors scheduled to begin operation once again in 2014. Currently, a space-based gravitational wave observatory known as the Laser Interferometer Space Antenna (LISA) has been proposed as a joint venture between NASA and the European Space Agency (ESA), and was originally expected to launch in 2015, but it is currently unknown if the project will continue due to tightening budgets. If completed, LISA will be the first space-based gravitational wave detector, and will use laser interferometers to monitor any changes in fluctuation in the distances between three points of the antenna in order to detect and measure passing gravitational waves.

On March 2014, physicists working at the Background Imaging of Cosmic Extragalactic Polarization 2 (BICEP2) experiment at the South Pole announced that gravitational waves had been detected. The team made the discovery while studying light polarization, the direction light waves travel, from just after the Big Bang in what is known as the Cosmic Microwave Background, which can be seen today as a faint glow of radiation throughout the sky [Moskowitz 2014]. The BICEP2 scientists found a pattern of light polarization that could only be produced

---

13 A binary star system consists of two stars orbiting around a common point called the center of mass. The primary star is the brighter of the two while the other is called the companion star.
by gravitational waves. During the first 380,000 years after the Big Bang, plasma in the young universe was too hot causing light to bounce off electrons until it was cool enough to allow light to spread through space. By studying how polarization interacted with that plasma, the BICEP2 team was able to confirm the detection of gravitational waves [Moskowitz 2014]. Gravitational waves passing through plasma as light bounces off from it causes photons to bounce at a 45 degree angle to the direction of hot and cold spots in the plasma. This is known as B-mode polarization. Because this is the first confirmation of gravitational wave detection, other experiments need to confirm the results before their existence can be confirmed.

5.3 A New Era of Giant Ground and Space Observatories

The Space Race during the Cold War was greatly responsible for growing support for astronomy by both the United States government and private agencies during the second half of the century. The funds made available for scientific research during the Cold War also involved the creation of astronomical instruments more powerful than any seen before. The last two decades have marked a new era in astronomy, one that began with the launch of the Hubble Space Telescope in 1990, followed by the establishment of the most powerful ground-based optical telescopes ever built, the Very Large Telescope in Chile and the Keck I and Keck II telescopes in Hawaii.

5.3.1 The Hubble Space Telescope

The Hubble space telescope has been extremely productive since its launch in 1990, and has taken some of the most publicly recognizable astronomical images. A space observatory was first proposed by German physicist Hermann Oberth (1984–1989) in 1923, but it would be another fifty years until efforts would be made to build a viable space-based telescope. Following the success of satellites launched in the late 1960s and early 1970s, NASA put
together a team to build a telescope that could conduct observations from space. Construction began in the early 1970s after Congress authorized funding. The Marshall Space Flight Center was selected by NASA to develop and build the telescope. The MSFC entrusted construction of the telescope’s support systems and final assembly to the Lockheed Missiles and Space Company in California, the development of its optical components were the responsibility of Connecticut based Perkin-Elmer Corporation, whereas the solar modules were built by the European Space Agency [Okolski 2008]. The mirror was completed in 1981, while the assembly of the telescope was completed in 1985, one year before its scheduled launch. The telescope’s operation control center was also completed in that same year. Once finished, Hubble measured 43 feet in height and weighed over 24,000 pounds. The telescope itself uses a modified Cassegrain reflector telescope with hyperbolic primary and secondary mirrors known as the Ritchey-Chretien reflector, originally developed in the early 1900s.14

The Hubble telescope consists of a 2.4-meter mirror with a focal length of 189 feet, and was designed to detect wavelengths in the visible, ultraviolet, and near-infrared regions [Okolski 2008]. The original instruments on the telescope have been regularly updated throughout the decades since its launch, and currently consist of an Advanced Camera for Surveys, a Cosmic Origins Spectrograph that studies the origin of the large scale structure of the universe, a Fine Guidance Sensor that controls the telescope’s Pointing Control System, a Near Infrared Camera and Multi-Object Spectrometer which is capable of providing images from a broad range of

14 The Ritchey-Chretien telescope was designed by American astronomer George Willis Ritchey and French astronomer Henri Chretien in the early 1910s. Its two hyperbolic mirror configuration was designed to eliminate optical aberrations, and became commonly used during the mid-twentieth century [King 1955: 354]. However, due to the high cost involved in casting hyperbolic mirrors, its use has been limited to high-performance telescopes such as the Very Large Telescope, the Keck I and Keck II telescopes, and the 10.4-meter Gran Telescopio Canarias in the Canary Islands.
wavelengths, the Space Telescope Imaging Spectrograph, and a fourth-generation Wide Field Camera.

Its original launch date, however, was postponed following the Challenger accident on January 28, 1986. Finally, on April 24, 1990, the Hubble Space Telescope was launched into orbit aboard the *Discovery* space shuttle, but within weeks after launch scientists discovered that the telescope’s mirror was flawed. Upon inspection of the first images taken, NASA engineers found that light from the edge and the center of the mirror were focusing in different areas of the lens, creating spherical aberration. Further investigation revealed that the mirror’s flaw was due to the fact that the Perkin-Elmer engineers had used a faulty template to polish the mirror, resulting in a mirror with the wrong curvature which caused spherical aberration [McCray 2004: 204].

Scientists and politicians could not understand why Hubble’s mirror had not been properly inspected, given that the original launch date had been postponed for four years. Congress had also become very critical of the project, considering that it cost over two billion dollars to build the telescope. Fortunately, the cameras on board the telescope were still able to detect images that allowed scientist to study astronomical bodies [Okolski 2008]. Replacing the mirror was not an option because of the high cost that would be involved with bringing the telescope back to Earth simply to replace its mirror. However, researchers were able to develop corrective lenses that acted as spectacles that could correct the spherical aberration detected. The corrective lenses were put in place during the first service mission to the telescope in December of 1993. Currently the Hubble Space Telescope produces over 120 gigabytes of data each week. For over two decades, Hubble has provided spectacular images that have shown humankind the
wonders of our universe in astonishing detail, while allowing astronomers to improve their knowledge of the cosmos.

The Hubble Space Telescope has greatly improved astronomers’ knowledge of the universe not only by taking some of the most recognizable pictures of space, but by revealing some of the hidden aspects of the universe as well. The Space telescope was used to construct the first three-dimensional map of dark matter. By observing how this invisible matter interacts and influences galaxy clusters and their light, astronomers have been able to study the distribution of dark matter. The three-dimensional model showed that galaxies, and other forms of matter, accumulate in areas with dense dark matter concentration [HubbleSite 2008]. The study of dark matter is important since it is believed to be the force responsible behind the acceleration of the universe’s expansion, however, one of Hubble’s main purposes prior to its launch was to help astronomers determine the age of the universe.

Prior to the launch of the space telescope, astronomers believed that the universe was anywhere between 10 to 20 billion years old. By using Hubble’s powerful mirror to capture and measure the light of numerous distant pulsating stars it is possible to determine their distance from Earth. Astronomers have calculated the age of the universe to an accuracy of approximately 5 percent estimating it to be 13.75 billion years old [HubbleSite 2008]. On September 25, 2012, NASA released the Hubble eXtreme Deep Field image showing galaxies 13.2 billion light-years away, an image that shows the universe shortly after the Big Bang, and further supporting the estimated age of the universe.

For a period of approximately ten years Nasa pointed the Hubble Space Telescope to a dark area in the constellation Fornax, and area chosen because it was free of galactic dust that might obstruct Hubble’s view. The resulting image, called the Hubble eXtreme Deep Field,
showed astronomers that galaxies evolved over time and even merged with other galaxies. As seen on Figure 21, every point of light shown on the Hubble Extreme Deep Field image is a galaxy, some of which were formed only 600 million years after the Big Bang [HubbleSite 2008].

![Figure 21](image)

**Figure 21.** Four iconic images taken by the Hubble Space Telescope. Starting at the top left corner with Jupiter’s red spots, which indicate storm clouds swirling across the planet. The top right image shows the ARP 273 galaxy collision. The bottom left image shows the Hubble Ultra Deep Field. Each point of light in the picture is a galaxy, some of which are located over 13 billion light years away. The last image shows interstellar gas and dust in the process of creating new stars, because of this, this image has become known as the “Pillars of Creation” [Hubblesite n.d.].

### 5.3.2 La Silla Observatory

Chile’s Arid Atacama desert is an excellent site for astronomy, and many astronomers agree that the views of the skies in the southern hemisphere are perhaps the most breathtaking in the world. Conditions in northern Chile are extremely favorable because the cold Humboldt Current flows northward along the coast minimizing atmospheric turbulence. Located at an altitude of 2400 meters in Northern Chile, the La Silla Observatory’s location provides it with clear skies far from sources of light pollution and has one of the darkest night skies on Earth.
providing more than 300 good observing nights per year. La Silla is the first European Southern Observatory (ESO), which was inaugurated in 1964 as the largest of its time. This marvel of modern engineering is home to several telescopes with mirrors measuring up to 3.6-meters in diameter and are among the most productive telescopes in the planet.

The New Technology Telescope (NTT) at La Silla was the first 3.6-meter telescope in the world to have an active optics computer controlled main mirror [McCray 2004: 180]. The 3.6-meter telescope houses the High Accuracy Radial Velocity Planet Searcher (HARPS), the world’s foremost extrasolar planet hunter. Although no longer the largest observatory in the world, La Silla is still one of the most scientifically productive. Along with the 67-million pixels Wide Field Imager on the MPG/ESO 2.2-meter telescope, La Silla is also home to a number of national telescopes including the 1.2-meter Swiss telescope and the 1.5-meter Danish telescope. The research being conducted at La Silla includes all aspects of astrophysics, asteroseismology, star formation, protoplanetary systems, and the search for extrasolar planets. Astronomers at La Silla have found numerous extrasolar planets including Gliese 581c, the first Earth like planet to be located in a habitable zone, located 20.5 light-years away [European Southern Observatory 2007]. Because of its privileged location, northern Chile became home to a number of international observatories. Since the 1960s, ESO has been building some of the world’s most technologically advanced observatories and developing the world’s biggest telescopes to go along them.

5.3.3 The Very Large Telescope

The ESO’s Very Large Telescope (VLT) is the world’s most advanced ground-based observatory, consisting of four 8.2-meter reflectors and four auxiliary 1.8-meter reflecting telescopes. The individual telescopes can detect objects with an apparent magnitude as faint as
30m. Additionally, the observatory was designed to integrate all telescopes to work together as an interferometer 25 times more powerful than any individual telescope by merging the radiation captured by multiple telescopes to act as one [European Southern Observatory 2012]. The 8.2-meter telescopes are enclosed in thermally controlled domes which are designed to rotate along with the telescope, and also consists of the most ambitious instrumentation program of any observatory ever built. These instruments include “large-field imagers, adaptive optics corrected cameras and spectrographs, as well as high-resolution and multi-object spectrographs” and cover a “broad spectral region, from deep ultraviolet (300 nm) to mid-infrared (24 µm) wavelengths” [European Southern Observatory 2012]. The VLT was the first observatory to produce an image of an extrasolar planet, and was the first to track stars moving around the supermassive black hole at the center of the Milky Way. The VLT observatory is located in an area which is considered to have the clearest skies on the planet at Cerro Paranal in the Chilean Atacama Desert.

5.3.4 The W. M. Keck Observatory

Located high on the summit of the Mauna Kea volcano in Hawaii, the W. M. Keck Observatory scans the skies with its twin 10-meter reflectors, both made up of 36 separate hexagonal segments, and are the largest optical telescopes in the world. The first Keck telescope, Keck I, saw first light in 1990, and was joined by its twin telescope, Keck II, in 1996, and are designed to work together by combining light captured by both telescopes. The Keck Observatory was a pioneer among modern observatories and introduced technologies that are now standard in observatories around the world.

The Keck Observatory was the first to make use of adaptive optics technology that corrects image distortion, an issue present in the performance of all ground based observatories
because of turbulence in the Earth’s atmosphere. Adaptive optics consists of a digitally controlled deformable mirror, the surface of which adapts to correct for atmospheric turbulence. The resulting images are about 10 times clearer than what was possible before the introduction of adaptive optics, but this technique requires a reference source, usually a close star with bright light, but there are not sufficient stars bright enough in the visible night sky which means that adaptive optics correction can only be done in a small percentage of sky. Scientists found that this problem could be resolved by creating an artificial star by pointing a laser into the atmosphere to excite sodium atoms. This has come to be known as laser-guide-star-adaptive-optics, and can be used to correct atmospheric turbulence at any part of the sky. The Keck Observatory was the first modern observatory to use this technology, and now produces images of greater sharpness than those produced even by the Hubble Space Telescope [Keck Observatory 2013].

Over the past two decades, the Keck Observatory has been responsible for a number of great discoveries. In 1998 while studying Type 1a supernovae, astronomers found that the universe was expanding much faster than previous measurements suggested. This provided evidence that some unknown force was responsible for the expansion’s acceleration, this force was called dark energy [Deeks 2013]. Along with dark energy, the Keck Observatory is also famous for providing astronomers with evidence of the existence of a supermassive black hole in the middle of our galaxy. By making use of its pioneering adaptive optics technology, University of California, Los Angeles astronomer, Andrea Ghez, was able to observe hundreds of stars orbiting in an elliptical orbit around the center of the Milky Way. By observing the distortion of the light and motion of stars while orbiting, Ghez was able to confirm the existence of a supermassive black hole in the center of our galaxy [Wolpert 2012].
5.4 How Technology Changed Astronomical Research in the Twentieth Century

The manner in which astronomical research is done has drastically changed over the last century, and will no doubt continue to change as more advanced technologies are developed. Astronomers who used to travel to select areas of the world in order to do their research have begun to see the inefficiency of this practice. Now scientists work in large survey groups that gather data which can be used by different astronomers around the world. The astronomer no longer sits in front of the telescope, but now sits at workbenches located in control rooms that are often located in separate buildings. Scientists from a number of different fields now work together to ensure that the instruments in the observatory properly collect the necessary data.

For many astronomers the “new observatories… represent[s] the closing of an era and, with it, a loss of the romance they associated with telescopic observing” [McCray 2004: 291]. For quite some time now the question within the older community of astronomers has been whether or not the new generation of telescopes is a bad thing for the astronomer as actual observation time has become limited due to high demand. Despite this, most agree that the new technologies have been important contributions to the advancement of astronomy, yet many of the older generation of astronomers prefer not to go to the new telescopes [McCray 2004: 291]. Research at observatories is now done by large teams that address common research problems rather than by the lone observer scanning across the skies. A typical night at a modern giant observatory like the ESO’s VLT in Chile involves a highly coordinated effort with different scientists using very different sets of skills with very specific defined roles. These giant telescopes are operated by groups of five or more people positioned in different areas of the console room, each of whom operates a different part of the telescope.
Astronomy has always been an observational science. During the Scientific Revolution the observational power of astronomy was greatly improved by various instruments such as the simple Galilean telescope, something that of course has continued to this day with the introduction of better imaging technology. As sociologist Karin Knorr Cetina observers, due to “the photographic plate with the help of which photons of light emitted by stellar bodies can be captured and analyzed,” astronomy has been transformed “from a science that surveys natural phenomena into a science which processes images of these phenomena” [Knorr-Cetina 1999: 27]. Photographic plates have now been replaced by charge-coupled devices (CCD), chips which allow astronomers to digitalize data in order to transfer and process information electronically. Technologies like CCD chips have removed the necessity for astronomers to observe the skies themselves, so it could be argued that what was for millennia essentially an observational science has now become an image-processing science. However, despite the fact that the astronomer’s place at the observatory is now at a workbench processing data gathered by computers rather than observing the skies, astronomy will continue to be an observational science. This aspect of the field will never truly disappear, it has simply moved from the eyepiece of the telescope to the monitor of a computer. Because of this, computer skills are required for all those who wish to study the large scale of the universe.

The revolutionary advances made in astronomy during the twentieth century were in large part due to the introduction of computers in the 1950s. Computers allowed scientists to process more data and develop more complex scientific modelling, allowing them to study the large scale of the universe. Modeling astronomical phenomena has always been an important tool for the astrophysicist, and with the aid of computers it is possible to create more models and generate more results in a fraction of the time needed previously. Computer modeling also
allows astronomers to formulate theories about phenomena that are otherwise impossible to study. For example, astrophysics professor at Rutgers University, Rachel Somerville, uses large supercomputers to create models of how certain gases come together to form stars and galaxies [Blesch 2013].

Computers can also collect and store more data than what was possible before, and that amount increases as more powerful computers are developed. In 2000, the Sloan Digital Sky Survey (SDSS), based at the Apache Point Observatory in New Mexico, started collecting data of the night sky, and since then it has captured 14,555 square degrees of the sky, roughly 35 percent [Sloan Digital Sky Survey 2013]. The SDSS utilizes a 2.5-meter telescope with a 120-megapixel camera and two spectrographs, and has created a picture of the night sky that can be analyzed digitally from anywhere in the world. Thanks to the SDSS, astronomers have been able to discover 26 of the 30 most distant quasars, galaxies with highly active centers, in the observable universe [Sloan Digital Sky Survey 2013]. Computers have given astronomers the ability to collect and share data at great speeds, but have also changed how astronomy is done.

Modern astronomers have become computer programmers in order to process the large amounts of data now being collected, but few have actual computer science training. During the past decades astronomy became a science that is dependent on cutting edge supercomputers, thus computer programming has become a skill that astronomers learn by practice as they do their jobs. For example, the Wide-Field Infrared Survey Explorer (WISE), NASA’s infrared wave length space telescope, generates approximately 7,000 images a day, which result in about 50 Gigabytes of data collected daily for a period of nine months. WISE requires a large team of astronomers and computer scientists to reduce this data into something usable. We are at the point where astronomy is done “by working with these massive data sets, looking for trends,
unusual objects, and comparing data from different surveys and telescopes that translates into programming” [Mainzer 2010]. The astronomer’s job can only begin after this data has been processed, so they must work together with computer programmers in order to make sense of the data collected by modern telescopes.

Of course there are great advantages that come with the new technologies being used in astronomy. Improvements in engineering, optics, and computer technology allow for improved angular resolutions, faster data processing, and the ability to observe objects at distances further away than ever before. This has enabled astronomers to study the large scale of the universe, dark matter, and the formation of galaxies. In other words, it has completely revolutionized astronomy. And just as it has been since Galileo redesigned the telescope, astronomers are still essential in the development of new technologies, since they are often actively involved in the design of new observatories by formulating the type of research questions future telescopes should help address.

As the output of astronomical data has become digitalized and astronomers have begun to make use of communally shared software, the sharing of data among scientists has become more effective. Software programs such as the Image Reduction and Analysis Facility (IRAF) reduce the large amounts of data collected by modern giant observatories into a common format that is available to all scientists through on-line archives. These not only offer “permanent resources for scientists,” but also “the potential of improved observatory management by allowing statistical studies of telescope use” [McCray 2004: 294].

For centuries scientists did astronomy by traveling to observatories, working alone at night, and collecting data. This is what astronomers call “classical observing.” Historian of science Patrick McCray argues that “astronomers who spent thousands of hours at the telescope
collecting data felt a strong emotional connection with this style of research, often describing the experience with masculine and idyllic imagery” [McCray 2004: 265]. But astronomers who practiced classical observation ran the risk of not being able to collect data in bad weather. Despite this, they still had control over the instruments they used. Astronomers had the freedom of pointing their telescopes wherever they wished to observe, rather than having to plan in advance. Modern observational astronomy lacks the freedom of quickly changing one’s agenda depending on the night. It is the job of the observatory staff to allocate observation time, and the order in which research projects are done. This form of “queue observation” has changed the nature of how astronomers’ research is done, since they no longer operate a telescope or collect data by themselves. Being an astronomer is now about waiting for data to be collected, and then spending hours examining it. Even though the older generation of astronomers maybe displeased about not being in direct control over their research, there is nothing that can be done about this if they wish to spend time in a modern twenty-first century observatory.

Perhaps the greatest example of how modern astronomical research is conducted involves NASA’s Hubble Space Telescope. Because the demand is so great for use of this telescope, in order to request observing time, an astronomer must first submit a Phase I proposal that will be reviewed by the staff of the Space Telescope Science Institute (STScI). Only about 20 percent of all submitted proposals are approved. If accepted, a Phase II observing program must be prepared listing what and where the astronomer wishes to observe. Once this information is sent to NASA, the staff at the Goddard Space Flight Center sends it to the telescope. The astronomer is not present during the data collecting process. Once that data is collected it is processed by the staff at the STScI. The data is first stored in the STScI archives before sending it to the astronomer. Scientists can use this data exclusively for one year before it is put in a public
archive, where it is made available to all scientists [McCray 2004: 269]. Considering that thousands of astronomers from around the world apply for time at observatories, this limits the extent to which astronomical research can be done by any one individual or project. However, almost all data gathered during research can now be easily shared among astronomers all over the world through what is known as a virtual observatory.

A virtual observatory utilizes a network of data archives and computer software to share astronomical research data over the internet. These observatories consist of collections of data centers with unique data, software, and processing capabilities. This allows information not to go to waste, and permits an astronomer to simply look for needed data rather than travel to an observatory that might require months, if not years, of planning. The main goals of virtual observatories are to unite astronomers around the world, to aid in the collection of data, and to turn this data into something comprehensible that can accessed by astronomers of all specializations regardless of the institution with which they are associated with [McCray 2004: 294]. Before the introduction of the internet, there was no effective way of sharing astronomical research among scientists at widely dispersed institutions. Data gathered at one observatory might be in a different language, different programming software might have been used, the vocabulary used could also have been different, it might even be in an unusual format, or the observatory could simply be located too far away. Starting in the year 2002, the International Virtual Observatory (IVOA), an organization comprised of nineteen virtual observatories from around the world, has facilitated international collaboration and communication between various countries [De Young 3: 2010]. Scientists are making use of technological developments to unite astronomers into one common digital universe that provides exchangeable data that is accessible to all that might need it.
The virtual observatory is simply one example that demonstrates one of the advantages of the evolution of technology in astronomy, which is a science that must continue to evolve technologically in order to meet the research demands of new generations of astronomers and astrophysicists. One of the current subjects of interest to many astronomers is dark matter. This type of matter cannot be seen with traditional telescopes as it does not emit light or any other form of electromagnetic radiation at detectable levels. It is believed that dark matter makes up a large part of the total mass of the universe, and thus it is fundamental in understanding its nature. However, because the current technology available to researchers cannot detect dark matter, new technologies need to be developed to enable the study and further understanding of this invisible matter. Astronomical instruments continue to become more sophisticated with every new observatory built, and this will continue with the next generation of telescopes already being designed.
Part VI: Future Technologies

The next couple of decades look very promising for astronomy, especially considering the great investments being made in the development of new technologies to help scientists better understand the universe. The ESO, with the advice of Europe’s leading astronomers, is currently designing the Extremely Large Telescope (ELT). Set for completion in 2022, the ELT observatory will contain a telescope with a 39-meter primary mirror, the largest ever built. Along with the ELT, two other giant telescopes are being planned to be operational within the next decade. The Giant Magellan Telescope (GMT) will have a 24.5-meter mirror and will be located in Chile along with the ESO’s Extremely Large Telescope. The GMT’s mirror will consist of seven separate mirrors of 8.4-meters, and the observatory’s total weight when completed will be around 1,100 tons [McKee 2013]. The Thirty Meter Telescope (TMT), as the name implies, will consist of a 30-meter mirror in diameter and will be located near the summit of Hawaii’s Mauna Kea volcano. Unlike the GMT, the TMT and the ELT will construct their mirrors by placing together hundreds of small hexagonal mirrors to form one giant mirror [McKee 2013]. These new telescopes are being designed to detect optical and near infrared wavelengths, and will serve the purpose of studying the new questions being asked by the astronomical community such as the nature and distribution of dark energy and dark matter. In 2018 NASA plans to launch the James Webb Space Telescope (JWST), named after NASA’s second administrator James E. Webb, as the successor to the Hubble Space Telescope. This 6.5-meter space telescope will search for light emitted shortly after the creation of the universe and will also study the formation of celestial objects. The year 2020 will see the largest astronomical survey ever conducted after the Large Synoptic Survey Telescope (LSST) sees its first light. Funded by the National Science Foundation, the LSST Corporation will begin construction of the LSST in 2014 atop Cerro
Pachón in Chile, and this will consist of an 8.4 meter telescope that will photograph the night sky for ten years.

Since ancient times humans have looked up to the sky and have attempted to explain the natural phenomena they observed. The last 400 years of technological developments have revolutionized astronomy, and have widened our understanding of the universe. The technologies developed during the nineteenth and twentieth centuries led to the emergence of new branches of astronomy, each dedicated to studying different aspect of an otherwise invisible universe. With new observatories and more advanced instruments constantly being developed, it is perhaps only a short matter of time before new revolutionary technologies change our perceptions of the universe once again. Technology has given us answers to many of the questions that have been asked for centuries, but with every discovery new questions arise. Perhaps we will never fully understand all of the mysteries of the universe, but new technologies will continue to be developed in order to reveal as much as possible.
References

American Institute of Physics. *The First Telescopes.*


Bothun, Gregory. “Towards Renaissance Cosmology.”
http://www.ned.ipac.caltech.edu/level5/bothun2/bothun1_1_3.html.


Cambridge University Library. *Footprints of the Lion: Isaac Newton at work.*
http://www.lib.cam.ac.uk/exhibitions/Footprints_of_the_Lion/private_scholar.html.


http://archive.cosmicdiary.org/blogs/nasa/amymainzer/?p=727  
Dr. Amy Mainzer is an astrophysicist and Wide-Field Infrared Survey Explorer (WISE) Deputy Project Scientist for NASA’s Jet Propulsion Laboratory at the California Institute of Technology.


McKee, Maggie. “The Race to Build the World’s Largest Telescope.” *Harvard University Graduate School of Arts and Sciences Bulletin* (March 11, 2013):  

Moskowitz, Clara. “Gravitational Waves from Big Bang Detected.” *Scientific American* (March 17, 2014):  

Nanjing University. *Space-Based Astronomy*.  


NASA History Program. *SP-402 a New Sun: The Solar Results from SkyLab*.  


History.nasa.gov/hubble/.


