LIVES IN ASTRONOMY

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INTRODUCTION[1]

Human history as cultural history

At present, history is taught as though power struggles were its most important aspect. Furthermore, the present teaching of history is an indoctrination in nationalism. We need to reform our teaching of history so that the emphasis will be placed on the gradual growth of human culture and knowledge, a growth to which all nations and ethnic groups have contributed.

This book is part of a series on cultural history. Here is a list of the other books in the series that have, until now, been completed:

- Lives in Chemistry
- Lives in Medicine
- Lives in Ecology
- Lives in Physics
- Lives in Economics
- Lives in the Peace Movement

The pdf files of these books may be freely downloaded and circulated from the following web address:

http://eacpe.org/about-john-scales-avery/

Our enormous universe

From prehistoric times until the present, every culture has tried to explain the origin of the universe, the Sun, Moon and stars, and the Earth, with its humans, plants and animals. In the earliest of these creation myths, imaginative poetical images predominate. The myths of creation were handed down orally, and to hold the attention of listeners, the stories had to be dramatic and entertaining.

Gradually, over many thousands of years, astronomy developed, and the Earth began to loose its privileged position as the center of the universe. During the Hellenistic Era, (323 B.C.-31 B.C.), Aristarchus of Samos developed a sun-centered cosmology, which was forgotten during the Middle Ages,

[1]This book makes some use of my previously published book chapters, but most of the material is new.

but rediscovered and further developed during the Renaissance by Copernicus, Tycho Brahe, Galileo and Kepler. The work of Isaac Newton brought order and universal natural laws into our picture of the solar system.

Finally, in modern times, the discoveries of Einstein, Hubble, Penzias and Wilson have given us a picture of an almost indescribably vast universe, in which our solar system appears only as an insignificant speck. Today we are “lost in the stars”. Our planet no longer seems to be the center of the universe, about which everything else revolves. Nevertheless, the Earth is our home, and it is enormously important not only to all humans, but also to the plants and animals with which we share the gift of life. The Earth may be just a small blue speck. drifting in the dark immensity of space, but it is our home, and we must work with courage and dedication to care for it. We must give our children a future world in which they can survive.

Chapter 1

EARLY HISTORY OF ASTRONOMY

1.1 Prehistoric Europe

Since 1990 our understanding of archeoastronomy in Europe has been radicaly changed bt the discovery of very ancient astronomical artifacts across the continent. Some of the discoveries listed by Wikipedia are the following:

- Paleolithic archaeologist Alexander Marshack put forward a theory in 1972 that bone sticks from locations like Africa and Europe from possibly as long ago as 35,000 BCE could be marked in ways that tracked the Moon's phases, an interpretation that has met with criticism.
- The Warren Field calendar in the Dee River valley of Scotland's Aberdeenshire. First excavated in 2004 but only in 2013 revealed as a find of huge significance, it is to date the world's oldest known calendar, created around 8000 BC and predating all other calendars by some 5,000 years. The calendar takes the form of an early Mesolithic monument containing a series of 12 pits which appear to help the observer track lunar months by mimicking the phases of the Moon. It also aligns to sunrise at the winter solstice, thus coordinating the solar year with the lunar cycles. The monument had been maintained and periodically reshaped, perhaps up to hundreds of times, in response to shifting solar/lunar cycles, over the course of 6,000 years, until the calendar fell out of use around 4,000 years ago.
- Goseck circle is located in Germany and belongs to the linear pottery culture. First discovered in 1991, its significance was only clear after results from archaeological digs became available in 2004. The site is one of hundreds of similar circular enclosures built in a region encompassing Austria, Germany, and the Czech Republic during a 200-year period starting shortly after 5000 BC.
- The Nebra sky disc is a Bronze Age bronze disc that was buried in Germany, not far from the Goseck circle, around 1600 BC. It measures about 30 cm diameter with a mass of 2.2 kg and displays a blue-green patina (from oxidization) inlaid with gold

symbols. Found by archeological thieves in 1999 and recovered in Switzerland in 2002, it was soon recognized as a spectacular discovery, among the most important of the 20th century. Investigations revealed that the object had been in use around 400 years before burial (2000 BC), but that its use had been forgotten by the time of burial. The inlaid gold depicted the full moon, a crescent moon about 4 or 5 days old, and the Pleiades star cluster in a specific arrangement forming the earliest known depiction of celestial phenomena. Twelve lunar months pass in 354 days, requiring a calendar to insert a leap month every two or three years in order to keep synchronized with the solar year's seasons (making it lunisolar). The earliest known descriptions of this coordination were recorded by the Babylonians in 6th or 7th centuries BC, over one thousand years later. Those descriptions verified ancient knowledge of the Nebra sky disc's celestial depiction as the precise arrangement needed to judge when to insert the intercalary month into a lunisolar calendar, making it an astronomical clock for regulating such a calendar a thousand or more years before any other known method.

- The Kokino site, discovered in 2001, sits atop an extinct volcanic cone at an elevation of 1,013 metres (3,323 ft), occupying about 0.5 hectares overlooking the surrounding countryside in North Macedonia. A Bronze Age astronomical observatory was constructed there around 1900 BC and continuously served the nearby community that lived there until about 700 BC. The central space was used to observe the rising of the Sun and full moon. Three markings locate sunrise at the summer and winter solstices and at the two equinoxes. Four more give the minimum and maximum declinations of the full moon: in summer, and in winter. Two measure the lengths of lunar months. Together, they reconcile solar and lunar cycles in marking the 235 lunations that occur during 19 solar years, regulating a lunar calendar. On a platform separate from the central space, at lower elevation, four stone seats (thrones) were made in north-south alignment, together with a trench marker cut in the eastern wall. This marker allows the rising Sun's light to fall on only the second throne, at midsummer (about July 31). It was used for ritual ceremony linking the ruler to the local sun god, and also marked the end of the growing season and time for harvest.
- Golden hats of Germany, France and Switzerland dating from 1400-800 BC are associated with the Bronze Age Urnfield culture. The Golden hats are decorated with a spiral motif of the Sun and the Moon. They were probably a kind of calendar used to calibrate between the lunar and solar calendars.[15][16] Modern scholarship has demonstrated that the ornamentation of the gold leaf cones of the Schifferstadt type, to which the Berlin Gold Hat example belongs, represent systematic sequences in terms of number and types of ornaments per band. A detailed study of the Berlin example, which is the only fully preserved one, showed that the symbols probably represent a lunisolar calendar. The object would have permitted the determination of dates or periods in both lunar and solar calendars.

Figure 1.1: **Stonehenge was used as an astronomical instrument to observe the time of the winter solstice, so that crops could be planted at the correct time. An even earlier version of Stonehenge, using wood instead of stone, has recently been discovered nearby. It dates back to approximately 8,000 BC.**

Figure 1.2: **An ancient astronomical observatory in India.**

Figure 1.3: **Another ancient astronomical observatory in India.**

Figure 1.4: **An ancient Chinease astronomical text.**

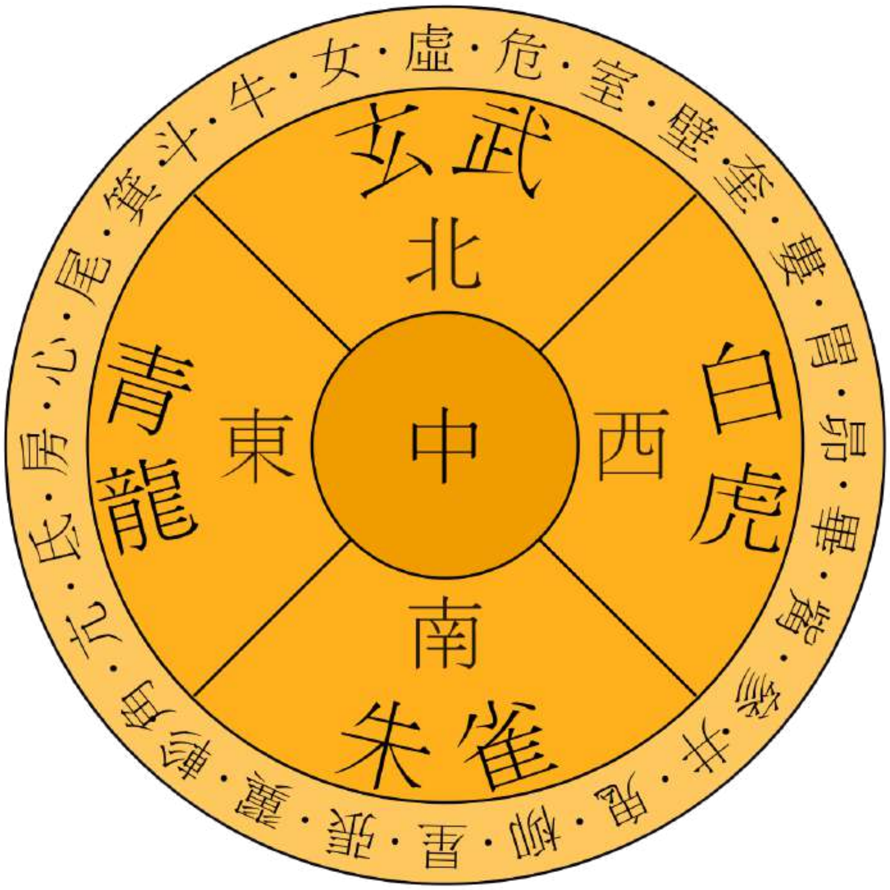

Figure 1.5: **The Twenty-Eight Mansions, a part of the Chinease constellations system. Wikepedia states thet "Ancient Chinese astronomers divided the sky ecliptic into four regions, collectively known as the Four Symbols, each assigned a mysterious animal. They are Azure Dragon on the east, Black Tortoise on the north, White Tiger on the west, and Vermilion Bird on the south. Each region contains seven mansions, making a total of 28 mansions. These mansions correspond to the longitudes along the ecliptic that the Moon crosses during its 27.32-day journey around the Earth and serve as a way to track the Moon's progress."**

1.2 Ancient India and China

Astronomy in ancient India has its roots in the Indus Valley Civilization, which began in approximately 3,300 BC. Astronomical observations were motivated by the need to perform religious ceremonies at the correct times of the year, and astronomy was closely connected with astrology. The sutras dealing with astronomy and mathematics were initially an oral tradition in the form of easily memorized verses, but were later written down together with commentaries. The oldest known written text is the Vedanga Jyotisha, dating from 1400-1200 BC.

Chinese astronomy dates back to the Shang Dynasty (second millenium BC). The mansion system organizing the constellations seems to have taken shape by the time that Wu Ding ruled China (1339-1281 BC). The ancient Chinese system of astronomy was based on especially close observation of stars near to the polar star. Joseph Needham describes Chinese astronomers as the most persistant and accurate observers of celestial phenomena anywhere in the world before the Islamic astronomers. Ancient Chinese observations of such phenomena as supernova are used today.

1.3 Mesopotamia, 4000 BC

In the imagination of the early Mesopotamians (the Sumerians, Elamites, Babylonians and Assyrians), the earth was a flat disc, surrounded by a rim of mountains and floating on an ocean of sweet water. Resting on these mountains was the hemispherical vault of the sky, across which moved the stars, the planets, the sun and the moon. Under the earth was another hemisphere containing the spirits of the dead. The Mesopotamians visualized the whole spherical world-universe as being immersed like a bubble in a limitless ocean of salt water.

By contrast with their somewhat primitive cosmology, both the mathematics and astronomy of the Mesopotamians were startlingly advanced. Their number system was positional, like ours, and was based on six and sixty. We can still see traces of it in our present method of measuring angles in degrees and minutes, and also in our method of measuring time in hours, minutes and seconds.

The Mesopotamians were acquainted with square roots and cube roots, and they could solve quadratic equations. They also were aware of exponential and logarithmic relationships. They seemed to value mathematics for its own sake, for the sake of enjoyment and recreation, as much as for its practical applications. On the whole, their algebra was more advanced than their geometry. They knew some of the properties of triangles and circles, but did not prove them in a systematic way.

Although the astronomy of the Mesopotamians was motivated largely by their astrological superstitions, it was nevertheless amazingly precise. For example, in the beginning of the fourth century B.C., incredibly accurate tables of new moons, full moons and eclipses were drawn up by Nabu-rimani; and about 375 B.C. Kidinnu, the greatest of the Babylonian astronomers, gave the exact duration of the solar year with an accuracy of only 4

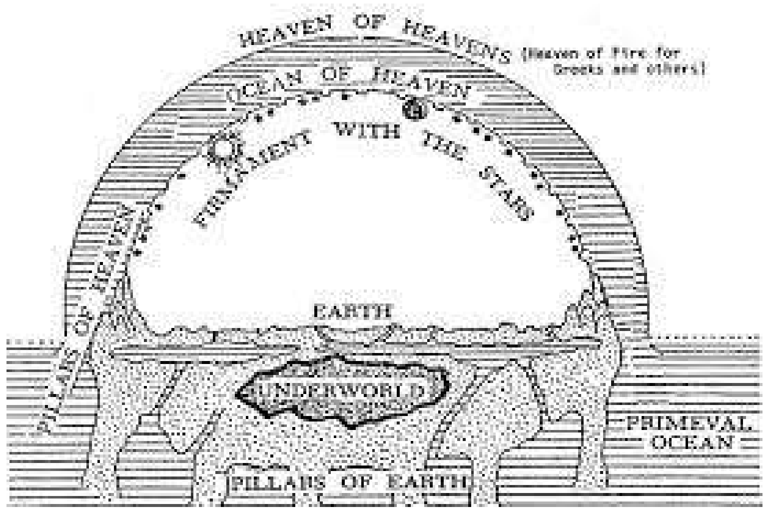

Figure 1.6: **Mesopotamian cosmology**

minutes and 32.65 seconds. (This figure was found by observing the accumulated error in the calender over a long period of time.) The error made by Kidinnu in his estimation of the motion of the sun from the node was smaller than the error made by the modern astronomer Oppolzer in 1887.

Thales of Miletus

It is known that the Greeks arrived in the Aegean region in three waves. The first to come were the Ionians. Next came the Achaeans, and finally the Dorians. Warfare between the Achaeans and the Ionians weakened both groups, and finally they both were conquered by the Dorians. This conquest by the semi-primitive Dorians was probably the event which brought the Mycenaean civilization to an end. At any rate, during the dark ages between 1,075 B.C. and 850 B.C., the art of writing was lost to the Greeks, and the level of artistic and cultural achievement deteriorated.

Beginning in about 850 B.C., there was a rebirth of Greek culture. This cultural renaissance began in Ionia on the west coast of present-day Turkey, where the Greeks were in close contact with the Babylonian civilization. Probably the Homeric epics were written in Miletus, a city on the coast of Asia Minor, in about 700 B.C.. The first three philosophers of the Greek world, Thales, Anaximander and Anaximenes, were also natives of Miletus.

Thales was born in 624 B.C. and died in 546 B.C.. The later Greeks considered him to have been the founder of almost every branch of knowledge. Whenever the wise men of ancient times were listed, Thales was invariably mentioned first. However, most of the achievements for which the Greeks admired Thales were probably not invented by him. He is supposed to have been born of a Phoenecian mother, and to have travelled extensively in Egypt and Babylonia, and he probably picked up most of his knowledge of science from

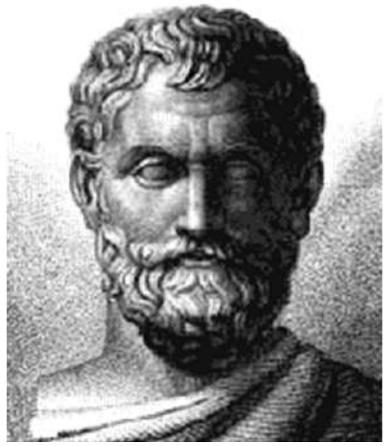

Figure 1.7: **Thales of Miletus.**

these ancient civilizations.

One of the achievements which made Thales famous was his prediction of a solar eclipse which (according to modern astronomers) occurred on May 28, 585 B.C.. On the day of the eclipse, the Medes and the Lydians were about to begin a battle, but the eclipse convinced them that they ought instead to make peace and return home. Thales predicted, not the exact day, but only the year in which the eclipse would occur, but nevertheless the Greeks were impressed. The astronomical knowledge which allowed him to make this prediction was undoubtedly learned from the Babylonians, who had developed a system for the accurate prediction of lunar eclipses two centuries earlier.

Thales brought Egyptian geometry to Greece, and he also made some original contributions to this field. He changed geometry from a set of *ad hoc* rules into an abstract and deductive science. He was the first to think of geometry as dealing not with real lines of finite thickness and imperfect straightness, but with lines of infinitessimal thickness and perfect straightness. (Echoes of this point of view are found in Plato's philosophy).

Thales speculated on the composition of matter, and decided that the fundamental element is water. He thought this because animals can live by eating plants, and plants (Thales mistakenly believed) can live on water without any other nourishment.

Many stories are told about Thales. For example, Aristotle says that someone asked Thales, "If you're so wise, why aren't you rich?" Thales was offended by this question, and in order to prove a point, he quietly bought up all the olive presses of the city during the winter of a year when his knowledge of weather told him that the olive harvest would be exceptionally large. When summer came, the harvest was enormous, and he was able to rent the presses at any price he liked to charge. He made himself rich in one season, and then went back to philosophy, having shown that philosophers could easily be rich if they liked, but they have higher ambitions than wealth.

Another story is told about Thales by Plato. According to Plato, Thales was so interested in some astronomical observations which he was making that he failed to look where he was going and fell into a well. He was helped out by a pretty and clever serving maid from Thrace who laughed at him because he was so interested in the stars that he could not see things that were right under his feet!

Thales had a student named Anaximander (610 B.C. - 546 B.C.) who also helped to bring Egyptian and Babylonian science to Greece. He imported the sundial from Egypt, and he was the first to try to draw a map of the entire world. He pictured the sky as a sphere, with the earth floating in space at its center. The sphere of the sky rotated once each day about an axis passing through the polar star. Anaximander knew that the surface of the earth is curved. He deduced this from the fact that as one travels northward, some stars disappear below the southern horizon, while others appear in the north. However, Anaximander thought that a north-south curvature was sufficient. He imagined the earth to be cylindrical rather than spherical in shape. The idea of a spherical earth had to wait for Pythagoras.

The third philosopher in the school of Militus was Anaximenes (570 B.C. - 500 B.C.), a pupil of Anaximander. He was the first of the Greeks to distinguish clearly between the planets and the stars. Like Thales, he speculated about the composition of matter, and he concluded that the fundamental element was air. This (he thought) could be compressed to form water, and still further compressed to form earth. Thus Anaximenes conceived in principle the modern idea of the three states of matter: gas, liquid and solid, which change into one another as the pressure and temperature are changed.

1.4 Ancient Egypt

The prosperity of ancient Egypt was based partly on its rich agriculture, nourished by the Nile, and partly on gold. Egypt possessed by far the richest gold deposits of the Middle East. They extended the whole length of the eastern desert, where more than a hundred ancient mines have been found; and in the south, Nubia was particularly rich in gold. The astonishing treasure found in the tomb of Tutankhamen, who was certainly not the most powerful of the pharaohs, gives us a pale idea of what the tombs of greater rulers must have been like before they were plundered.

In the religion of ancient Egypt, the distinction between the gods and the pharaohs was never very clear. Living pharaohs were considered to be gods, and they traced their ancestry back to the sun-god, Ra. Since all of the pharaohs were thought to be gods, and since, before the unification of Egypt, there were very many local gods, the Egyptian religion was excessively complicated. A list of gods found in the tomb of Thuthmosis III enumerates no fewer than seven hundred and forty! The extreme conservatism of Egyptian art (which maintained a consistent style for several thousand years) derives from the religious function played by painting and sculpture.

The famous gods, Osiris, Isis, Horus and Set probably began their existence as real people, and their story, which we know both from hieroglyphic texts and from Pliny, depicts an actual historical event - the first unification of Egypt: Osiris, the good ruler of

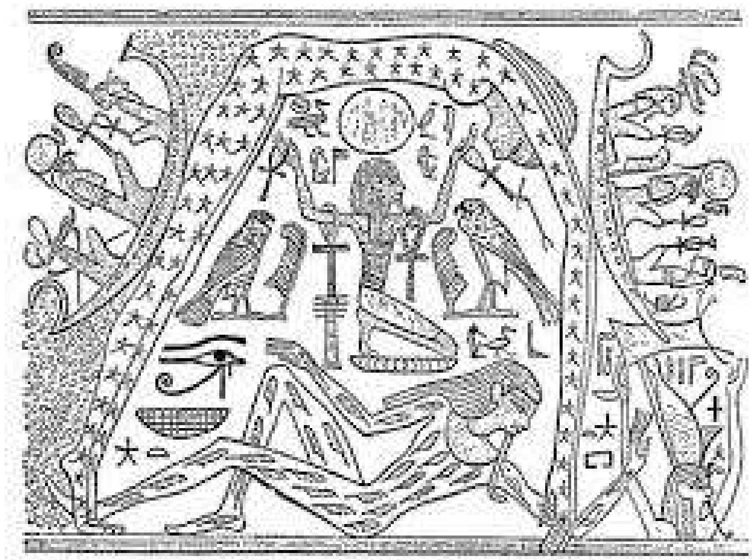

Figure 1.8: **In the imagery of the ancient Egyptians, the goddess Nut represented the sky, while her husband, Geb, was the earth.**

the lower Nile, was murdered and cut to pieces by his jealous brother Set; but the pieces of Osiris' body were collected by his faithful wife Isis, who performed the first mummification and thus made Osiris immortal. Then Horus, the son of Osiris and Isis, like an Egyptian Hamlet, avenged the murder of his father by tracking down his wicked uncle Set, who attempted to escape by turning into various animals. However, in the end Horus killed Set, and thus Horus became the ruler of all of Egypt, both the lower Nile and the upper Nile.

This first prehistoric unification of Egypt left such a strong impression on the national consciousness that when a later pharaoh named Menes reunified Egypt in 3,200 B.C., he did so in the name of Horus. Like the Mesopotamian story of the flood, and like the epics of Homer, the story of the unification of Egypt by Horus probably contains a core of historical fact, blended with imaginative poetry. At certain points in the story, the characters seem to be real historical people - for example, when Osiris is described as being "handsome, dark-skinned and taller than other men". At other times, imagination seems to predominate. For example, the goddess Nut, who was the mother of Osiris, was thought to be the sky, while her husband Geb was the earth. The long curved body of Nut was imagined to be arched over the world so that only the tips of her toes and fingers touched the earth, while the stars and moon moved across her belly. Meanwhile her husband Geb lay prostrate, with all the vegetation of the earth growing out of his back.

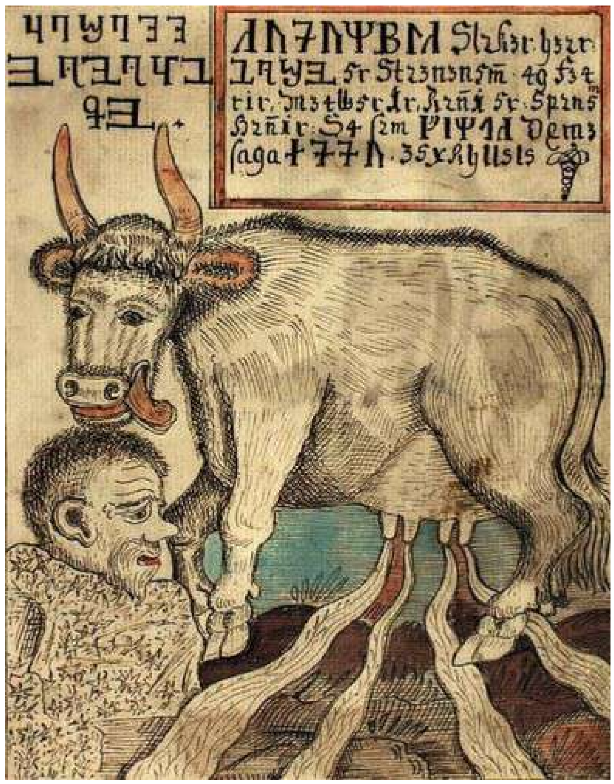

Figure 1.9: **The Nordic myth of the creation of the universe: "Thawing frost then became a cow called Audhumla. Four rivers of milk ran from her teats, and she fed Ymir. The cow licked salty ice blocks. After one day of licking, she freed a man's hair from the ice. After two days, his head appeared. On the third day the whole man was there. His name was Buri, and he was tall, strong, and handsome."**

Figure 1.10: **Ancient Nordic cosmology: "As all informed people know, the gods built a bridge from earth to heaven called Bifröst. Some call it the rainbow. It has three colors and is very strong, made with more skill and cunning than other structures. But strong as it is, it will break when the sons of Muspell ride out over it. The gods are not to blame that this structure will then break. Bifröst is a good bridge, but there is nothing in this world that can be relied on when the sons of Muspell are on the warpath. The chief sanctuary of the gods is by the ash tree Yggdrasil. There they hold their daily court. Yggdrasil is the best and greatest of all trees. Its branches spread out over the whole world and reach up over heaven."**

1.5 Eratosthenes

Eratosthenes (276 B.C. - 196 B.C.), the director of the library at Alexandria, was probably the most cultured man of the Hellenistic Era. His interests and abilities were universal. He was an excellent historian, in fact the first historian who ever attempted to set up an accurate chronology of events. He was also a literary critic, and he wrote a treatise on Greek comedy. He made many contributions to mathematics, including a study of prime numbers and a method for generating primes called the "sieve of Eratosthenes".

As a geographer, Eratosthenes made a map of the world which, at that time, was the most accurate that had ever been made. The positions of various places on Eratosthenes' map were calculated from astronomical observations. The latitude was calculated by measuring the angle of the polar star above the horizon, while the longitude probably was calculated from the apparent local time of lunar eclipses.

As an astronomer, Eratosthenes made an extremely accurate measurement of the angle between the axis of the earth and the plane of the sun's apparent motion; and he also prepared a map of the sky which included the positions of 675 stars.

Eratosthenes' greatest achievement however, was an astonishingly precise measurement of the radius of the earth. The value which he gave for the radius was within 50 miles of what we now consider to be the correct value! To make this remarkable measurement, Eratosthenes of course assumed that the earth is spherical, and he also assumed that the sun is so far away from the earth that rays of light from the sun, falling on the earth, are almost parallel. He knew that directly south of Alexandria there was a city called Seyne, where at noon on a midsummer day, the sun stands straight overhead. Given these facts, all he had to do to find the radius of the earth was to measure the distance between Alexandria and Seyne. Then, at noon on a midsummer day, he measured the angle which the sun makes with the vertical at Alexandria. From these two values, he calculated the circumference of the earth to be a little over 25,000 miles. This was so much larger than the size of the known world that Eratosthenes concluded (correctly) that most of the earth's surface must be covered with water; and he stated that "If it were not for the vast extent of the Atlantic, one might sail from Spain to India along the same parallel."

1.6 Aristarchus

The Hellenistic astronomers not only measured the size of the earth - they also measured the sizes of the sun and the moon, and their distances from the earth. Among the astronomers who worked on this problem was Aristarchus (c. 320 B.C. - c. 250 B.C.). Like Pythagoras, he was born on the island of Samos, and he may have studied in Athens under Strato. However, he was soon drawn to Alexandria, where the most exciting scientific work of the time was being done.

Aristarchus calculated the size of the moon by noticing the shape of the shadow of the earth thrown on the face of the moon during a solar eclipse. From the shape of the earth's shadow, he concluded that the diameter of the moon is about a third the diameter of the earth. (This is approximately correct).

From the diameter of the moon and the angle between its opposite edges when it is seen from the earth, Aristarchus could calculate the distance of the moon from the earth. Next he compared the distance from the earth to the moon with the distance from the earth to the sun. To do this, he waited for a moment when the moon was exactly half-illuminated. Then the earth, moon and sun formed a right triangle, with the moon at the corner corresponding to the right angle. Aristarchus, standing on the earth, could measure the angle between the moon and the sun. He already knew the distance from the earth to the moon, so now he knew two angles and one side of the right triangle. This was enough to allow him to calculate the other sides, one of which was the sun-earth distance. His value for this distance was not very accurate, because small errors in measuring the angles were magnified in the calculation.

Aristarchus concluded that the sun is about twenty times as distant from the earth as the moon, whereas in fact it is about four hundred times as distant. Still, even the underestimated distance which Aristarchus found convinced him that the sun is enormous! He calculated that the sun has about seven times the diameter of the earth, and three hundred and fifty times the earth's volume. Actually, the sun's diameter is more than a hundred times the diameter of the earth, and its volume exceeds the earth's volume by a factor of more than a million!

Even his underestimated value for the size of the sun was enough to convince Aristarchus that the sun does not move around the earth. It seemed ridiculous to him to imagine the enormous sun circulating in an orbit around the tiny earth. Therefore he proposed a model of the solar system in which the earth and all the planets move in orbits around the sun, which remains motionless at the center; and he proposed the idea that the earth spins about its axis once every day.

Although it was the tremendous size of the sun which suggested this model to Aristarchus, he soon realized that the heliocentric model had many calculational advantages: For example, it made the occasional retrograde motion of certain planets much easier to explain. Unfortunately, he did not work out detailed table for predicting the positions of the planets. If he had done so, the advantages of the heliocentric model would have been so obvious that it might have been universally adopted almost two thousand years before the time of Copernicus, and the history of science might have been very different.

Aristarchus was completely right, but being right does not always lead to popularity. His views were not accepted by the majority of astronomers, and he was accused of impiety by the philosopher Cleanthes, who urged the authorities to make Aristarchus suffer for his heresy. Fortunately, the age was tolerant and enlightened, and Aristarchus was never brought to trial.

The model of the solar system on which the Hellenistic astronomers finally agreed was not that of Aristarchus but an alternative (and inferior) model developed by Hipparchus (c. 190 B.C. - c. 120 B.C.). Hipparchus made many great contributions to astronomy and mathematics. For example, he was the first person to calculate and publish tables of trigonometric functions. He also invented many instruments for accurate naked-eye observations. He discovered the "precession of equinoxes", introduced a classification of stars according to their apparent brightness, and made a star-map which far outclassed the earlier star-map of Eratosthenes. Finally, he introduced a model of the solar system which allowed fairly accurate calculation of the future positions of the planets, the sun and the moon.

In English, we use the phrase “wheels within wheels” to describe something excessively complicated. This phrase is derived from the model of the solar system introduced by Hipparchus! In his system, each planet has a large wheel which revolves with uniform speed about the earth (or in some cases, about a point near to the earth). Into this large wheel was set a smaller wheel, called the “epicycle”, which also revolved with uniform speed. A point on the smaller wheel was then supposed to duplicate the motion of the planet. In some cases, the model of Hipparchus needed still more “wheels within wheels” to duplicate the planet’s motion.. The velocities and sizes of the wheels were chosen in such a way as to “save the appearances”.

The model of Hipparchus was popularized by the famous Egyptian astronomer, Claudius Ptolemy (c. 75 A.D. - c. 135 A.D.), in a book which dominated astronomy up to the time of Copernicus. Ptolemy’s book was referred to by its admirers as *Megale Mathematike Syntaxis* (The Great Mathematical Composition). During the dark ages which followed the fall of Rome, Ptolemy’s book was preserved and translated into Arabic by the civilized Moslems, and its name was shortened to *Almagest* (The Greatest). It held the field until, in the 15th century, the brilliant heliocentric model of Aristarchus was rescued from oblivion by Copernicus.

Figure 1.11: **A map of the known world by Eratosthenes, surrounded by spheres on which moved the sun, moon and stars.**

Figure 1.12: **A statue of Aristarchus. In the background we see his sun-centered picture of planetary motion.**

Suggestions for further reading

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Chapter 2

COPERNICUS, BRAHE, KEPLER AND GALILEO

2.1 Copernicus

The career of Leonardo da Vinci illustrates the first phase of the "information explosion" which has produced the modern world: Inexpensive paper was being manufactured in Europe, and it formed the medium for Leonardo's thousands of pages of notes. His notes and sketches would never have been possible if he had been forced to use expensive parchment as a medium. On the other hand, the full force of Leonardo's genius and diligence was never felt because his notes were not printed.

Copernicus, who was a younger contemporary of Leonardo, had a much greater effect on the history of ideas, because his work was published. Thus, while paper alone made a large contribution to the information explosion, it was printing combined with paper which had an absolutely decisive and revolutionary impact: The modern scientific era began with the introduction of printing.

Nicolas Copernicus (1473-1543) was orphaned at the age of ten, but fortunately for science he was adopted by his uncle, Lucas Watzelrode, the Prince-Bishop of Ermland (a small semi-independent state which is now part of Poland). Through his uncle's influence, Copernicus was made a Canon of the Cathedral of Frauenberg in Ermland at the age of twenty-three. He had already spent four years at the University of Krakow, but his first act as Canon was to apply for leave of absence to study in Italy.

At that time, Italy was very much the center of European intellectual activity. Copernicus stayed there for ten years, drawing a comfortable salary from his cathedral, and wandering from one Italian University to another. He studied medicine and church law at Padua and Bologna, and was made a Doctor of Law at the University of Ferrara. Thus, thanks to the influence of his uncle, Copernicus had an education which few men of his time could match. He spent altogether fourteen years as a student at various universities, and he experienced the bracing intellectual atmosphere of Italy at the height of the Renaissance.

Figure 2.1: **Nicolas Copernicus (1473-1543).**

In 1506, Bishop Lucas recalled Copernicus to Ermland, where the young Canon spent the next six years as his uncle's personal physician and administrative assistant. After his uncle's death, Copernicus finally took up his duties as Canon at the cathedral-fortress of Frauenberg on the Baltic coast of Ermland; and he remained there for the rest of his life, administering the estates of the cathedral, acting as a physician to the people of Ermland, and working in secret on his sun-centered cosmology.

Even as a student in Krakow, Copernicus had thought about the problem of removing the defects in the Ptolomeic system. In Italy, where the books of the ancient philosophers had just become available in the original Greek, Copernicus was able to search among their writings for alternative proposals. In Ptolemy's system, not all the "wheels within wheels" turn with a uniform velocity, although it is possible to find a point of observation called the *"punctum equans"* from which the motion seems to be uniform. Concerning this, Copernicus wrote:

"A system of this sort seems neither sufficiently absolute, nor sufficiently pleasing to the mind... Having become aware of these defects, I often considered whether there could be found a more reasonable arrangement of circles, in which everything would move uniformly about its proper center, as the rule of absolute motion requires.."

While trying to remove what he regarded as a defect in the Ptolemeic system by re-arranging the wheels, Copernicus rediscovered the sun-centered cosmology of Aristarchus. However, he took a crucial step which went beyond Aristarchus: What Copernicus did during the thirty-one years which he spent in his isolated outpost on the Baltic was to develop the heliocentric model into a complete system, from which he calculated tables of planetary positions.

The accuracy of Copernicus' tables was a great improvement on those calculated from the Ptolemeic system, and the motions of the planets followed in a much more natural way. The inner planets, Mercury and Venus, stayed close to the sun because of the smallness of their orbits, while the occasional apparently retrograde motion of the outer planets could be explained in a very natural way by the fact that the more rapidly-moving earth sometimes overtook and passed one of the outer planets. Furthermore, the speed of the planets diminished in a perfectly regular way according to their distances from the sun.

According the the Copernican cosmology, the earth moves around the sun in an orbit whose radius is ninety-three million miles. As the earth moves in its enormous orbit, it is sometimes closer to a particular star, and sometimes farther away. Therefore the observed positions of the stars relative to each other ought to change as the earth moves around its orbit. This effect, called "stellar parallax", could not be observed with the instruments which were available in the 16th century.

The explanation which Copernicus gave for the absence of stellar parallax was that "Compared to the distance of the fixed stars, the earth's distance from the sun is neglegibly small!" If this is true for the nearest stars, then what about the distance to the farthest stars?

Vast and frightening chasms of infinity seemed to open under the feet of those who understood the implications of the Copernican cosmology. Humans were no longer rulers of a small, tidy universe especially created for themselves. They were suddenly "lost in the stars", drifting on a tiny speck of earth through unimaginably vast depths of space. Hence the cry of Blaise Pascal: *"Le silence eternal de ce éspaces infinis m'effraie!"*, "The eternal silence of these infinite spaces terrifies me!"

2.2 Tycho Brahe

The next step in the Copernican revolution was taken by two men who presented a striking contrast to one another. Tycho Brahe (1546-1601) was a wealthy and autocratic Danish nobleman, while Johannes Kepler (1571-1630) was a neurotic and poverty-stricken teacher in a provincial German school. Nevertheless, in spite of these differences, the two men collaborated for a time, and Johannes Kepler completed the work of Tycho Brahe.

At the time when Tycho was born, Denmark included southern Sweden; and ships sailing to and from the Baltic had to pay a toll as they passed through the narrow sound between Helsingør (Elsinore) in Denmark, and Helsingborg in what is now Sweden. On each side of the sound was a castle, with guns to control the sea passage. Tycho Brahe's father, a Danish nobleman, was Governor of Helsingborg Castle.

Tycho's uncle was also a military man, a Vice-Admiral in the navy of the Danish king, Frederik II. This uncle was childless, and Tycho's father promised that the Vice-Admiral could adopt one of his own children. By a fortunate coincidence, twins were born to the Governor's wife. However, when one of the twins died, Tycho's father was unwilling to part with the survivor (Tycho). The result was that, in the typically high-handed style of the Brahe family, the Vice-Admiral kidnapped Tycho. The Governor at first threatened murder, but soon calmed down and accepted the situation with good grace.

The adoption of Tycho Brahe by his uncle was as fortunate for science as the adoption of Copernicus by Bishop Watzelrode, because the Vice-Admiral soon met his death in an heroic manner which won the particular gratitude of the Danish Royal Family:

Admiral Brahe, returning from a battle against the Swedes, was crossing a bridge in the company of King Frederik II. As the king rode across the bridge, his horse reared suddenly, throwing him into the icy water below. The king would have drowned if Admiral Brahe had not leaped into the water and saved him. However, the Admiral saved the king's life at the cost of his own. He caught pneumonia and died from it. The king's gratitude to Admiral Brahe was expressed in the form of special favor shown to his adopted son, Tycho, who had in the meantime become an astronomer (against the wishes of his family).

As a boy of fourteen, Tycho Brahe had witnessed a partial eclipse of the sun, which had been predicted in advance. It struck him as "something divine that men could know the motions of the stars so accurately that they were able a long time beforehand to predict their places and relative positions". Nothing that his family could say would dissuade him from studying astronomy, and he did so not only at the University of Copenhagen, but also at Leipzig, Wittenberg, Rostock, Basel and Augsberg.

During this period of study, Tycho began collecting astronomical instruments. His lifelong quest for precision in astronomical observation dated from his seventeenth year, when he observed a conjunction of Saturn and Jupiter. He found that the best tables available were a month in error in predicting this event. Tycho had been greatly struck by the fact that (at least as far as the celestial bodies were concerned), it was possible to predict the future; but here the prediction was in error by a full month! He resolved to do better.

Tycho first became famous among astronomers through his observations on a new star, which suddenly appeared in the sky in 1572. He used the splendid instruments in his collection to show that the new star was very distant from the earth - certainly beyond the sphere of the moon - and that it definitely did not move with respect to the fixed stars. This was, at the time, a very revolutionary conclusion. According to Aristotle, (who was still regarded as the greatest authority on matters of natural philosophy), all generation and decay should be confined to the region beneath the sphere of the moon. Tycho's result meant that Aristotle could be wrong!

Tycho thought of moving to Basel. He was attracted by the beauty of the town, and he wanted to be nearer to the southern centers of culture. However, in 1576 he was summoned to appear before Frederik II. Partly in recognition of Tycho's growing fame as an astronomer, and partly to repay the debt of gratitude which he owed to Admiral Brahe, the king made Tycho the ruler of Hven, an island in the sound between Helsingborg and Helsingør. Furthermore, Frederik granted Tycho generous funds from his treasury to construct an observatory on Hven.

With these copious funds, Tycho Brahe constructed a fantastic castle-observatory which he called Uranieborg. It was equipped not only with the most precise astronomical instruments the world had ever seen, but also with a chemical laboratory, a paper mill, a printing press and a dungeon for imprisoning unruly tenants.

Tycho moved in with a retinue of scientific assistants and servants. The only thing which he lacked was his pet elk. This beast had been transported from the Brahe estate at Knudstrup to Landskrona Castle on the Sound, and it was due to be brought on a boat to the island of Hven. However, during the night, the elk wandered up a stairway

Figure 2.2: **Tycho Brahe.**

in Landskrona Castle and found a large bowl of beer in an unoccupied room. Like its master, the elk was excessively fond of beer, and it drank so much that, returning down the stairway, it fell, broke its leg, and had to be shot.

Tycho ruled his island in a thoroughly autocratic and grandiose style, the effect of which was heightened by his remarkable nose. In his younger days, Tycho had fought a duel with another student over the question of who was the better mathematician. During the duel, the bridge of Tycho's nose had been sliced off. He had replaced the missing piece by an artificial bridge which he had made of gold and silver alloy, and this was held in place by means of a sticky ointment which he always carried with him in a snuff box.

Tycho entertained in the grandest possible manner the stream of scholars who came to Hven to see the wonders of Uranieborg. Among his visitors were King James VI of Scotland (who later ascended the English throne as James I), and the young prince who later became Christian IV of Denmark.

With the help of his numerous assistants, Tycho observed and recorded the positions of the sun, moon, planets and stars with an accuracy entirely unprecedented in the history of astronomy. He corrected both for atmospheric refraction and for instrumental errors,

Figure 2.3: **Tycho Brahe's large mural quadrant at Uranieborg.**

Figure 2.4: **Johannes Kepler**

with the result that his observations were accurate to within two minutes of arc. This corresponds to the absolute limit of what can be achieved without the help of a telescope.

Not only were Tycho's observations made with unprecedented accuracy - they were also made *continuously* over a period of 35 years. Before Tycho's time, astronomers had haphazardly recorded an observation every now and then, but no one had thought of making systematic daily records of the positions of each of the celestial bodies. Tycho was able to make a "motion picture" record of the positions of the planets because he could divide the work among his numerous assistants.

All went well with Tycho on the island of Hven for twelve years. Then, in 1588, Frederik II died (of alcoholism), and his son ascended the throne as Christian IV. Frederik II had been especially grateful to Admiral Brahe for saving his life, and he treated the Admiral's adopted son, Tycho, with great indulgence. However, Christian IV was unwilling to overlook the increasingly scandalous and despotic way in which Tycho was ruling Hven; and he reduced the subsidies which Tycho Brahe had been receiving from the royal treasury. The result was that Tycho, feeling greatly insulted, dismantled his instruments and moved them to Prague, together with his retinue of family, scientific assistants, servants and jester.

In Prague, Tycho became the Imperial Mathematician of the Holy Roman Emperor, Rudolph II. (We should mention in passing that royal patrons such as Rudolph were more interested in astrology than in astronomy: The chief duty of the Imperial Mathematician was to cast horoscopes for the court!) After the move to Prague, one of Tycho's senior scientific assistants became dissatisfied and left. To replace him, Tycho recruited a young German mathematician named Johannes Kepler.

2.3 Johannes Kepler

Two thousand years before the time of Kepler, Pythagoras had dreamed of finding mathematical harmony in the motions of the planets. Kepler and Newton were destined to fulfil his dream. Kepler was also a true follower of Pythagoras in another sense: Through his devotion to philosophy, he transcended the personal sufferings of a tortured childhood and adolescence. He came from a family of misfits whose neurotic quarrelsomeness was such that Kepler's father narrowly escaped being hanged, and his mother was accused of witchcraft by her neighbors. She was imprisoned, and came close to being burned.

At the age of 4, Kepler almost died of smallpox, and his hands were badly crippled. Concerning his adolescence, Kepler wrote: "I suffered continually from skin ailments, often severe sores, often from the scabs of chronic putrid wounds in my feet, which healed badly and kept breaking out again. On the middle finger of my right hand, I had a worm, and on the left, a huge sore."

Kepler's mental strength compensated for his bodily weakness. His brilliance as a student was quickly recognized, and he was given a scholarship to study theology at the University of Tübingen. He was agonizingly lonely and unpopular among his classmates.

Kepler distinguished himself as a student at Tübingen, and shortly before his graduation, he was offered a post as a teacher of mathematics and astronomy at the Protestant School in Graz. With the post went the title of "Mathematician of the Provence of Styria". (Gratz was the capital of Styria, a province of Austria).

Johannes Kepler was already an ardent follower of Copernicus; and during the summer of his first year in Graz, he began to wonder why the speed of the planets decreased in a regular way according to their distances from the sun, and why the planetary orbits had the particular sizes which Copernicus assigned to them.

On July 9, 1595, in the middle of a lecture which he was giving to his class, Kepler was electrified by an idea which changed the entire course of his life. In fact, the idea was totally wrong, but it struck Kepler with such force that he thought he had solved the riddle of the universe with a single stroke!

Kepler had drawn for his class an equilateral triangle with a circle circumscribed about it, so that the circle passed through all three corners of the triangle. Inside, another circle was inscribed, so that it touched each side of the triangle. It suddenly struck Kepler that the ratio between the sizes of the two circles resembled the ratio between the orbits of Jupiter and Saturn. His mercurial mind immediately leaped from the two-dimensional figure which he had drawn to the five regular solids of Pythagoras and Plato.

In three dimensions, only five different completely symmetrical many-sided figures are possible: the tetrahedron, cube, octahedron, icosahedron and the dodecahedron. There the list stops. As Euclid proved, it is a peculiarity of three-dimensional space that there are only five possible regular polyhedra. These five had been discovered by Pythagoras, and they had been popularized by Plato, the most famous of the Pythagorean philosophers. Because Plato made so much of the five regular solids in his dialogue *Timaeus*, they became known as the "Platonic solids".

In a flash of (completely false) intuition, Kepler saw why there had to be exactly six planets: The six spheres of the planetary orbits were separated by the five Platonic solids! This explained the sizes of the orbits too: Each sphere except the innermost and the outermost was inscribed in one solid and circumscribed about another!

Kepler, who was then twenty-three years old, was carried away with enthusiasm. He immediately wrote a book about his discovery and called it *Mysterium Cosmographicum*, "The Celestial Mystery". The book begins with an introduction strongly supporting the Copernican cosmology. After that comes the revelation of Kepler's marvelous (and false) solution to the cosmic mystery by means of the five Platonic solids. Kepler was unable to make the orbit of Jupiter fit his model, but he explains naively that "nobody will wonder at it, considering the great distance". The figures for the other planets did not quite fit either, but Kepler believed that the distances given by Copernicus were inaccurate.

Finally, after the mistaken ideas of the book, comes another idea, which comes close to the true picture of gravitation. Kepler tries to solve the problem of why the outer planets move more slowly than the inner ones, and he says:

"If we want to get closer to the truth and establish some correspondence in the proportions, then we must choose between these two assumptions: Either the souls of the planets are less active the farther they are from the sun, or there exists only one moving soul in the center of the orbits, that is the sun, which drives the planets the more vigorously the closer the planet is, but whose force is quasi-exhausted when acting on the outer planets, because of the long distance and the weakening of the force which it entails."

In *Mysterium Cosmographicum*, Kepler tried to find an exact mathematical relationship between the speeds of the planets and the sizes of their orbits; but he did not succeed in this first attempt. He finally solved this problem many years later, towards the end of his life.

Kepler sent a copy of his book to Tycho Brahe with a letter in which he called Tycho "the prince of mathematicians, not only of our time, but of all time". Tycho was pleased with this "fan letter"; and he recognized the originality of Kepler's book, although he had reservations about its main thesis.

Meanwhile, religious hatred had been deepening and Kepler, like all other Protestants, was about to be expelled from Catholic Austria. He appealed to Tycho for help, and Tycho, who was in need of a scientific assistant, wrote to Kepler from the castle of Benatek near Prague:

"You have no doubt already been told that I have most graciously been called here by his Imperial Majesty and that I have been received in a most friendly and benevolent manner. I wish that you would come here, not forced by the adversity of fate, but rather of your own will and desire for common study. But whatever your reason, you will find in me your friend, who will not deny you his advice and help in adversity"

To say that Kepler was glad for this opportunity to work with Tycho Brahe is to put the matter very mildly. The figures of Copernicus did not really fit Kepler's model, and his great hope was that Tycho's more accurate observations would give a better fit. In his less manic moments, Kepler also recognized that his model might not be correct after all, but he hoped that Tycho's data would allow him to find the true solution.

Kepler longed to get his hands on Tycho's treasure of accurate data, and concerning these he wrote:

"Tycho possesses the best observations, and thus so-to-speak the material for building the new edifice. He also has collaborators, and everything else he could wish for. He only lacks the architect who would put all this to use according to his own design. For although he has a happy disposition and real architectural skill, he is nevertheless obstructed in his progress by the multitude of the phenomena, and by the fact that the truth is deeply hidden in them. Now old age is creeping upon him, enfeebling his spirit and his forces"

In fact, Tycho had only a short time to live. Kepler arrived in Prague in 1600, and in 1601 he wrote:

"On October 13, Tycho Brahe, in the company of Master Minkowitz, had dinner at the illustrious Rosenborg's table, and held back his water beyond the demands of courtesy. When he drank more, he felt the tension in his bladder increase, but he put politeness before health. When he got home, he was scarcely able to urinate.. After five sleepless nights, he could still only pass water with the greatest pain, and even so the passage was impeded. The insomnia continued, with internal fever gradually leading to delirium; and the food which he ate, from which he could not be kept, exacerbated the evil... On his last night, he repeated over and over again, like someone composing a poem: 'Let me not seem to have lived in vain'."

A few days after Tycho's death, Kepler was appointed to succeed him as Imperial Mathematician of the Holy Roman Empire. Kepler states that the problem of analyzing Tycho's data took such a hold on him that he nearly went out of his mind. With a fanatic diligence rarely equaled in the history of science, he covered thousands of pages with calculations. Finally, after many years of struggle and many false starts, he wrung from Tycho's data three precise laws of planetary motion:

1) The orbits of the planets are ellipses, with the sun at one focal point.

2) A line drawn from the sun to any one of the planets sweeps out equal areas in equal intervals of time.

3) The square of the period of a planet is proportional to the cube of the mean radius of its orbit.

Thanks to Kepler's struggles, Tycho certainly had not lived in vain. Kepler's three laws were to become the basis for Newton's great universal laws of motion and gravitation. Kepler himself imagined a universal gravitational force holding the planets in their orbits around the sun, and he wrote:

"If two stones were placed anywhere in space, near to each other, and outside the reach of force of any other material body, then they would come together after the manner of magnetic bodies, at an intermediate point, each approaching the other in proportion to the other's mass... "

"If the earth ceased to attract the waters of the sea, the seas would rise up and flow to the moon... If the attractive force of the moon reaches down to the earth, it follows that the attractive force of the earth, all the more, extends to the moon, and even farther... "

"Nothing made of earthly substance is absolutely light; but matter which is less dense, either by nature or through heat, is relatively lighter... Out of the definition of lightness follows its motion; for one should not believe that when lifted up it escapes to the periphery of the world, or that it is not attracted to the earth. It is merely less attracted than heavier matter, and is therefore displaced by heavier matter."

Kepler also understood the correct explanation of the tides. He explained them as being produced primarily by the gravitational attraction of the moon, while being influenced to a lesser extent by the gravitational field of the sun.

Unfortunately, when Kepler published these revolutionary ideas, he hid them in a tangled jungle of verbiage and fantasy which repelled the most important of his readers, Galileo Galilei. In fact, the English were the first to appreciate Kepler. King James I (whom Tycho entertained on Hven) invited Kepler to move to England, but he declined the invitation. Although the skies of Europe were darkened by the Thirty Years War, Kepler could not bring himself to leave the German cultural background where he had been brought up and where he felt at home.

2.4 Galileo

Experimental physics

Galileo Galilei was born in Pisa in 1564. He was the son of Vincenzo Galilei, an intellectual Florentine nobleman whose fortune was as small as his culture was great. Vincenzo Galilei was a mathematician, composer and music critic, and from him Galileo must have learned independence of thought, since in one of his books Vincenzo wrote: “It appears to me that those who try to prove a assertion by relying simply on the weight of authority act very absurdly.” This was to be Galileo’s credo throughout his life. He was destined to demolish the decayed structure of Aristotelian physics with sledgehammer blows of experiment.

Vincenzo Galilei, who knew what it was like to be poor, at first tried to make his son into a wool merchant. However, when Galileo began to show unmistakable signs of genius, Vincenzo decided to send him to the University of Pisa, even though this put a great strain on the family’s financial resources.

At the university and at home, Galileo was deliberately kept away from mathematics. Following the wishes of his father, he studied medicine, which was much better paid than mathematics. However, he happened to hear a lecture on Euclid given by Ostilio Ricci, a friend of his father who was Mathematician at the court of the Grand Duke Ferdinand de’ Medici.

Galileo was so struck by the logical beauty and soundness of the lecture that he begged Ricci to lend him some of the works of Euclid. These he devoured in one gulp, and they were followed by the works of Archimedes. Galileo greatly admired Archimedes’ scientific method, and he modeled his own scientific method after it.

After three years at the University of Pisa, Galileo was forced to return home without having obtained a degree. His father had no more money with which to support him, and Galileo was unable to obtain a scholarship, probably because his irreverent questioning of every kind of dogma had made him unpopular with the authorities. However, by this time he had already made his first scientific discovery.

According to tradition, Galileo is supposed to have made this discovery while attending a service at the Cathedral of Pisa. His attention was attracted to a lamp hung from the vault, which the verger had lighted and left swinging. As the swings became smaller, he noticed that they still seemed to take the same amount of time. He checked this by timing the frequency against his pulse. Going home, he continued to experiment with pendula. He found that the frequency of the oscillations is independent of their amplitude, provided that the amplitude is small; and he found that the frequency depends only on the length of the pendulum.

Having timed the swings of a pendulum against his pulse, Galileo reversed the procedure and invented an instrument which physicians could use for timing the pulse of a patient. This instrument consisted of a pendulum whose length could be adjusted until the swings matched the pulse of the patient. The doctor then read the pulse rate from the calibrated length of the pendulum. Galileo's pulse meter was quickly adopted by physicians throughout Europe. Later, the famous Dutch physicist, Christian Huygens (1629-1695), developed Galileo's discovery into the pendulum clock as we know it today.

While he was living at home after leaving the University of Pisa, Galileo invented a balance for measuring specific gravity, based on Archimedes' Principle in hydrostatics.

Through his writings and inventions, particularly through his treatise on the hydrostatic balance, Galileo was becoming well known, and at the age of 26 he was appointed Professor of Mathematics at the University of Pisa. However, neither age nor the dignity of his new title had mellowed him. As a professor, he challenged authority even more fiercely than he had done as a student. He began systematically checking all the dogmas of Aristotle against the results of experiment.

Aristotle had asserted that the speed of a falling object increased according to its weight: Thus, according to Aristotle, an object ten times as heavy as another would fall ten times as fast. This idea was based on the common experience of a stone falling faster than a feather.

Galileo realized that the issue was being complicated by air resistance. There were really two questions to be answered: 1) How would a body fall in the absence of air? and 2) What is the effect of air resistance? Galileo considered the first question to be the more fundamental of the two, and in order to answer it, he experimented with falling weights made of dense materials, such as iron and lead, for which the effect of air resistance was reduced to a minimum.

According to Galileo's student and biographer, Viviani, Galileo, wishing to refute Aristotle, climbed the Leaning Tower of Pisa in the presence of all the other teachers and philosophers and of all the students, and "by repeated experiments proved that the velocity of falling bodies of the same composition, unequal in weight, does not attain the proportion of their weight as Aristotle assigned it to them, but rather that they move with equal velocity." (Some historians doubt Viviani's account of this event, since no mention of it appears in other contemporary sources.)

Galileo maintained that, in a vacuum, a feather would fall to the ground like a stone. This experiment was not possible in Galileo's time, but later it was tried, and Galileo's prediction was found to be true.

Galileo realized that falling bodies gain in speed as they fall, and he wished to find a quantitative law describing this acceleration. However, he had no good method for measuring very small intervals of time. Therefore he decided to study a similar process which was slow enough to measure: He began to study the way in which a ball, rolling down an inclined plane, increases in speed.

Describing these experiments, Galileo wrote:

"..Having placed the board in a sloping position... we rolled the ball along the channel, noting , in a manner presently to be described, the time required to make the descent. We repeated the experiment more than once, in order to measure the time with an accuracy such that the deviation between two observations never exceeded one-tenth of a pulse beat"

"Having performed this operation, and having assured ourselves of its reliability, we now rolled the ball only one quarter of the length of the channel, and having measured the time of its descent, we found it precisely one-half the former. Next we tried other distances, comparing the time for the whole length with that for the half, or with that for two-thirds or three-fourths, or indeed any fraction. In such experiments, repeated a full hundred times, we always found that the spaces traversed were to each other as the squares of the times..."

"For the measurement of time, we employed a large vessel of water placed in an elevated position. To the bottom of this vessel was soldered a pipe of small diameter giving a thin jet of water, which we collected in a small glass during the time of each descent... The water thus collected was weighed after each descent on a very accurate balance. The differences and ratios of these weights gave us the differences and ratios of the times, and with such an accuracy that although the operation was repeated many, many times, there was no appreciable discrepancy in the results"

These experiments pointed to a law of motion for falling bodies which Galileo had already guessed: The acceleration of a falling body is constant; the velocity increases in linear proportion to the time of fall; and the distance traveled increases in proportion to the square of the time.

Extending these ideas and experiments, Galileo found that a projectile has two types of motion superimposed: the uniformly accelerated falling motion just discussed, and, at the same time, a horizontal motion with uniform velocity. He showed that, neglecting air resistance, these two types of motion combine to give the projectile a parabolic trajectory.

Galileo also formulated the principle of inertia, a law of mechanics which states that in the absence of any applied force, a body will continue at rest, or if in motion, it will continue indefinitely in uniform motion. Closely related to this principle of inertia is the principle of relativity formulated by Galileo and later extended by Einstein: Inside a closed room, it is impossible to perform any experiment to determine whether the room is at rest, or whether it is in a state of uniform motion.

For example, an observer inside a railway train can tell whether the train is in motion by looking out of the window, or by the vibrations of the car; but if the windows were covered and the tracks perfectly smooth, there would be no way to tell. An object dropped in a uniformly-moving railway car strikes the floor directly below the point from which it was dropped, just as it would do if the car were standing still.

The Galilean principle of relativity removed one of the objections which had been raised against the Copernican system. The opponents of Copernicus argued that if the earth really were in motion, then a cannon ball, shot straight up in the air, would not fall back on the cannon but would land somewhere else. They also said that the birds and the

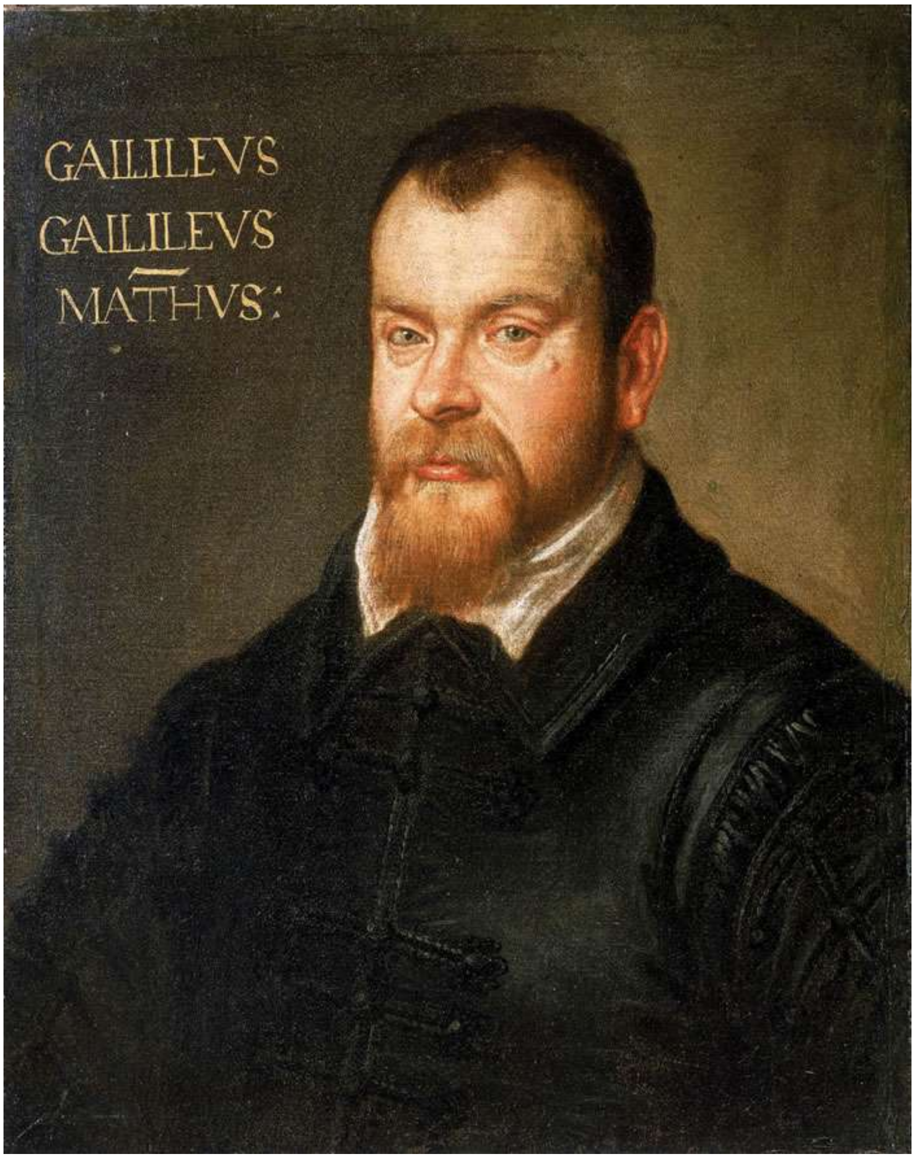

Figure 2.5: **Galileo Galilei in a portrait by Domenico Tintoretto.**

clouds would be left behind by the motion of the earth.

In 1597, Kepler sent Galileo a copy of his *Mysterium Cosmographicum*. Galileo read the introduction to the book, which was the first printed support of Copernicus from a professional astronomer, and he replied in a letter to Kepler:

"...I shall read your book to the end, sure of finding much that is excellent in it. I shall do so with the more pleasure because I have for many years been an adherent of the Copernican system, and it explains to me the causes of many of the phenomena of nature which are quite unintelligible on the commonly accepted hypothesis."

"I have collected many arguments in support of the Copernican system and refuting the opposite view, which I have so far not ventured to make public for fear of sharing the fate of Copernicus himself, who, though he acquired immortal fame with some, is yet to an infinite multitude of others (for such is the number of fools) an object of ridicule and derision. I would certainly publish my reflections at once if more people like you existed; as they don't, I shall refrain from publishing."

Kepler replied urging Galileo to publish his arguments in favor of the Copernican system:

"...Have faith, Galileo, and come forward! If my guess is right, there are but few among the prominent mathematicians of Europe who would wish to secede from us, for such is the force of truth." However, Galileo left Kepler's letter unanswered, and he remained silent concerning the Copernican system.

By this time, Galileo was 33 years old, and he had become Professor of Mathematics at the University of Padua. His Aristotelian enemies at the University of Pisa had succeeded in driving him out, but by the time they did so, his fame had become so great that he was immediately offered a position at three times the salary at Padua.

The move was a very fortunate one for Galileo. Padua was part of the free Venetian Republic, outside the power of the Inquisition, and Galileo spent fifteen happy and productive years there. He kept a large house with a master mechanic and skilled craftsmen to produce his inventions (among which was the thermometer). His lectures were attended by enthusiastic audiences, sometimes as large as two thousand; and he had two daughters and a son with a Venetian girl.

The telescope

In 1609, news reached Galileo that a Dutch optician had combined two spectacle lenses in such a way as to make distant objects seem near. Concerning this event, Galileo wrote:

"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. Of this truly remarkable effect, several experiences were related, to which some persons gave credence while others denied them."

"A few days later the report was confirmed to me in a letter from (a former pupil) at Paris; which caused me to apply myself wholeheartedly to inquire into the means by which I might arrive at the invention of a similar instrument. This I did shortly afterward through deep study of 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. Then, placing my eye near the concave lens, I perceived objects satisfactorally large and near, for they appeared three times closer and nine times larger than when seen with the naked eye alone."

"Next I constructed another more accurate instrument, which represented objects as enlarged more than sixty times. Finally, sparing neither labor nor expense, I succeeded in constructing for myself an instrument so excellent that objects seen through it appeared nearly one thousand times larger and over thirty times closer than when regarded with our natural vision."

Galileo showed one of his early telescopes to his patrons, the Signoria of Venice. Writing of this, Galileo says:

"Many noblemen and senators, though of advanced age, mounted to the top of one of the highest towers to watch the ships, which were visible through my glass two hours before they were seen entering the harbor; for it makes a thing fifty miles off as near and clear as if it were only five."

The senate asked Galileo whether he would give the city a similar instrument to aid in its defense against attack by sea. When he did this, they immediately doubled his salary, and they confirmed him in his position for life.

After perfecting the telescope as much as he could, Galileo turned it towards the moon, the planets and the stars. He made a series of revolutionary discoveries which he announced in a short booklet called *Siderius Nuncius*, (The Siderial Messenger). The impact of this booklet was enormous, as can be judged by the report of Sir Henry Wotton, the British Ambassador to Venice:

"Now touching the occurents of the present", Sir Henry wrote, "I send herewith to His Majesty the strangest piece of news (as I may justly call it) that he has ever yet received from any part of the world; which is the annexed book (come abroad this very day) of the Mathematical Professor at Padua, who by the help of an optical instrument (which both enlargeth and approximateth the object) invented first in Flanders and bettered by himself, hath discovered four new planets rolling around the sphere of Jupiter, besides many other unknown fixed stars; likewise the true cause of the *Via Lactae* (Milky Way), so long searched; and lastly that the moon is not spherical but endued with many prominences, and, which is strangest of all, illuminated with the solar light by reflection from the body of the earth, as he seemeth to say. So as upon the whole subject, he hath overthrown all former astronomy.."

"These things I have been so bold to discourse unto your Lordship, whereof here all corners are full. And the author runneth a fortune to be either exceeding famous or exceeding ridiculous. By the next ship your Lordship shall receive from me one of the above instruments, as it is bettered by this man."

Wherever Galileo turned his powerful telescope, he saw myriads of new stars, so utterly outnumbering the previously known stars that mankind's presumption to know anything at all about the universe suddenly seemed pitiful. The Milky Way now appeared as a sea of stars so numerous that Galileo despaired of describing them in detail. The vastness of the universe as postulated by Nicolas Copernicus and Gordiano Bruno (one ridiculed and the other burned alive) was now brought directly to Galileo's senses. In fact, everywhere he looked he saw evidence supporting the Copernican system and refuting Aristotle and Ptolemy.

The four moons of Jupiter, which Galileo had discovered, followed the planet in its motion, thus refuting the argument that if the earth revolved around the sun, the moon would not be able to revolve around the earth. Also, Jupiter with its moons formed a sort of Copernican system in miniature, with the massive planet in the center and the four small moons circling it, the speed of the moons decreasing according to their distance from Jupiter.

Galileo discovered that the planet Venus has phase changes like the moon, and that these phase changes are accompanied by changes in the apparent size of the planet. Copernicus had predicted that if the power of human vision could be improved, exactly these changes in the appearance of Venus would be observed. Galileo's observations proved that Venus moves in an orbit around the sun: When it is on the opposite side of the sun from the earth, it appears small and full; when it lies between the earth and the sun, it is large and crescent.

Galileo also observed mountains on the moon. He measured their height by observing the way in which sunlight touches their peaks just before the lunar dawn, and he found some of the peaks to be several miles high. This disproved the Aristotelian doctrine that the moon is a perfect sphere, and it established a point of similarity between the moon and the earth.

Galileo observed that the dark portion of the moon is faintly illuminated, and he asserted that this is due to light reflected from the earth, another point of similarity between the two bodies. Generally speaking, the impression which Galileo gained from his study of the moon is that it is a body more or less like the earth, and that probably the same laws of physics apply on the moon as on the earth.

All these observations strongly supported the Copernican system, although the final rivet in the argument, the observation of stellar parallax, remained missing until the 19th century. Although he did not possess this absolutely decisive piece of evidence, Galileo thought that he had a strong enough basis to begin to be more open in teaching the Copernican system. His booklet, *Siderius Nuncius* had lifted him to an entirely new order of fame. He had seen what no man had ever seen before, and had discovered new worlds. His name was on everyone's lips, and he was often compared to Colombus.

Still it moves

In 1610, Galileo left Padua to take up a new post as Mathematician to the court of the Medicis in Florence; and in the spring of 1611, he made a triumphal visit to Rome. Describing this visit, Cardinal del Monte wrote: "If we were living under the ancient Republic of Rome, I really believe that there would have been a column on the Capital erected in Galileo's honor!" The Pope received Galileo in a friendly audience, and Prince Cesi made him a member of the Adademia dei Lincei.

The Jesuit astronomers were particularly friendly to Galileo. They verified his observations and also improved some of them. However, Galileo made many enemies, especially among the entrenched Aristotelian professors in the universities. He enjoyed controversy (and publicity), and he could not resist making fools of his opponents in such a way that they often became bitter personal enemies.

Not only did Galileo's law describing the acceleration of falling bodies contradict Aristotle, but his principle of inertia contradicted the Aristotelian dogma, *omne quod movetur ab alio movetur* - whatever moves must be moved by something else. (The Aristotelians believed that each planet is moved by an angel.) Galileo also denied Aristotle's teaching that generation and decay are confined to the sphere beneath the orbit of the moon.

Although Galileo was at first befriended and honored by the Jesuit astronomers, he soon made enemies of the members of that order through a controversy over priority in the discovery of sunspots. In spite of this controversy, Galileo's pamphlet on sunspots won great acclaim; and Cardinal Maffeo Barberini (who later became Pope Urban VIII) wrote to Galileo warmly praising the booklet.

In 1613, the Medicis gave a dinner party and invited Professor Castelli, one of Galileo's students who had become Professor of Mathematics at Pisa. After dinner, the conversation turned to Galileo's discoveries, and the Grand Duchess Christina, mother of Duke Cosimo de' Medici, asked Castelli his opinion about whether the motion of the earth contradicted the Bible.

When this conversation was reported to Galileo, his response was to publish a pamphlet entitled *Letter to Castelli*, which was later expanded into a larger pamphlet called *Letter to the Grand Duchess Christina*. These pamphlets, which were very widely circulated, contain the following passage:

"...Let us grant, then, that Theology is conversant with the loftiest divine contemplation, and occupies the regal throne among the sciences by this dignity. By acquiring the highest authority in this way, if she does not descend to the lower and humbler speculations of the subordinate sciences, and has no regard for them because they are not concerned with blessedness, then her professors should not arrogate to themselves the authority to decide on controversies in professions which they have neither studied nor practiced. Why this would be as if an absolute despot, being neither a physician nor an architect, but knowing himself free to command, should undertake to administer medicines and erect buildings according to his whim, at the grave peril of his poor patients' lives, and the speedy collapse of his edifices..."

Galileo's purpose in publishing these pamphlets was to overcome the theological objections to the Copernican system. The effect was exactly the opposite. The *Letter to Castelli* was brought to the attention of the Inquisition, and in 1616 the Inquisition prohibited everyone, especially Galileo, from holding or defending the view that the earth turns on its axis and moves in an orbit around the sun.

Galileo was silenced, at least for the moment. For the next eighteen years he lived unmolested, pursuing his scientific research. For example, continuing his work in optics, he constructed a compound microscope.

In 1623, marvelous news arrived: Cardinal Maffio Barberini had been elected Pope. He was a great intellectual, and also Galileo's close friend. Galileo went to Rome to pay his respects to the new Pope, and he was received with much warmth. He had six long audiences with the Pope, who showered him with praise and gifts. The new Pope refused to revoke the Inquisition's decree of 1616, but Galileo left Rome with the impression that he was free to discuss the Copernican system, provided he stayed away from theological arguments.

Galileo judged that the time was right to bring forward his evidence for the Copernican cosmology; and he began working on a book which was to be written in the form of a Platonic dialogue. The characters in the conversation are Salivati, a Copernican philosopher, Sagredo, a neutral but intelligent layman, and Simplicio, a slightly stupid Aristotelian, who always ends by losing the arguments.

The book, which Galileo called *Dialogue on the Two Chief World Systems*, is a strong and only very thinly veiled argument in favor of the Copernican system. When it was published in 1632, the reaction was dramatic. Galileo's book was banned almost immediately, and the censor who had allowed it to be printed was banished in disgrace. When the agents of the Inquisition arrived at the bookstores to confiscate copies of the *Dialogue*, they found that the edition had been completely sold out.

The Pope was furious. He felt that he had been betrayed. Galileo's enemies had apparently convinced the Pope that the character called Simplicio in the book was a caricature of the Pope himself! Galileo, who was seventy years old and seriously ill, was dragged to Rome and threatened with torture. His daughter, Maria Celeste, imposed severe penances and fasting on herself, thinking that these would help her prayers for her father. However, her health was weak, and she became ill.

Meanwhile, Galileo, under threat of torture, had renounced his advocacy of the motion of the earth. According to tradition, as he rose from his knees after the recantation he muttered *"Eppur si muove!"*, ("Still it moves!") It is unlikely that he muttered anything of the kind, since it would have been fatally dangerous to do so, and since at that moment, Galileo was a broken man. Nevertheless, the retort which posterity has imagined him to make remains unanswerable. As Galileo said, before his spirit was broken by the Inquisition, "...It is not in the power of any creature to make (these ideas) true or false or otherwise than of their own nature and in fact they are."

Galileo was allowed to visit the bedside of his daughter, Marie Celeste, but in her weak condition, the anxiety of Galileo's ordeal had been too much for her. Soon afterward, she died. Galileo was now a prisoner of the Inquisition. He used his time to write a book on his lifelong work on dynamics and on the strength of material structures. The manuscript of this book, entitled *Two New Sciences*, was smuggled out of Italy and published in Holland.

When Galileo became blind, the Inquisition relaxed the rules of his imprisonment, and he was allowed to have visitors. Many people came to see him, including John Milton, who was then 29 years old. One wonders whether Milton, meeting Galileo, had any premonition of his own fate. Galileo was already blind, while Milton was destined to become so. The two men had another point in common: their eloquent use of language. Galileo was a many-sided person, an accomplished musician and artist as well as a great scientist. The impact of his ideas was enhanced by his eloquence as a speaker and a writer. This can be seen from the following passage, taken from Galileo's *Dialogue*, where Sagredo comments on the Platonic dualism between heavenly perfection and earthly corruption:

"...I cannot without great wonder, nay more, disbelief, hear it being attributed to natural bodies as a great honor and perfection that they are impassable, immutable, inalterable, etc.; as, conversely, I hear it esteemed a great imperfection to be alterable, generable and mutable. It is my opinion that the earth is very noble and admirable by reason of the many different alterations, mutations and generations which incessantly occur in it. And if, without being subject to any alteration, it had been one vast heap of sand, or a mass of jade, or if, since the time of the deluge, the waters freezing that covered it, it had continued an immense globe of crystal, whereon nothing had ever grown, altered or changed, I should have esteemed it a wretched lump of no benefit to the Universe, a mass of idleness, and in a word, superfluous, exactly as if it had never been in Nature. The difference for me would be the same as between a living and a dead creature."

"I say the same concerning the moon, Jupiter and all the other globes of the Universe. The more I delve into the consideration of the vanity of popular discourses, the more empty and simple I find them. What greater folly can be imagined than to call gems, silver and gold noble, and earth and dirt base? For do not these persons consider that if there were as great a scarcity of earth as there is of jewels and precious metals, there would be no king who would not gladly give a heap of diamonds and rubies and many ingots of gold to purchase only so much earth as would suffice to plant a jasmine in a little pot or to set a tangerine in it, that he might see it sprout, grow up, and bring forth such goodly leaves, fragrant flowers and delicate fruit?"

The trial of Galileo cast a chill over the intellectual atmosphere of southern Europe, and it marked the end of the Italian Renaissance. However, the Renaissance had been moving northward, and had produced such figures as Dürer and Gutenberg in Germany, Erasmus and Rembrandt in Holland, and Shakespeare in England. In 1642, the same year during which Galileo died in Italy, Isaac Newton was born in England.

Suggestions for further reading

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3. Stillman Drake, *Galileo, Pioneer Scientist*, Toronnto University Press, (1990).
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Chapter 3

NEWTON

3.1 Newton

On Christmas day in 1642 (the year in which Galileo died), a recently widowed woman named Hannah Newton gave birth to a premature baby at the manor house of Woolsthorpe, a small village in Lincolnshire, England. Her baby was so small that, as she said later, "he could have been put into a quart mug", and he was not expected to live. He did live, however, and lived to achieve a great scientific synthesis, uniting the work of Copernicus, Brahe, Kepler, Galileo and Descartes.

When Isaac Newton was four years old, his mother married again and went to live with her new husband, leaving the boy to be cared for by his grandmother. This may have caused Newton to become more solemn and introverted than he might otherwise have been. One of his childhood friends remembered him as "a sober, silent, thinking lad, scarce known to play with the other boys at their silly amusements".

As a boy, Newton was fond of making mechanical models, but at first he showed no special brilliance as a scholar. He showed even less interest in running the family farm, however; and a relative (who was a fellow of Trinity College) recommended that he be sent to grammar school to prepare for Cambridge University.

When Newton arrived at Cambridge, he found a substitute father in the famous mathematician Isaac Barrow, who was his tutor. Under Barrow's guidance, and while still a student, Newton showed his mathematical genius by inventing the binomial theorem.

In 1665, Cambridge University was closed because of an outbreak of the plague, and Newton returned for two years to the family farm at Woolsthorpe. He was then twenty-three years old. During the two years of isolation, Newton developed his binomial theorem into the beginnings of differential calculus.

Newton's famous experiments in optics also date from these years. The sensational experiments of Galileo were very much discussed at the time, and Newton began to think about ways to improve the telescope. Writing about his experiments in optics, Newton says:

"In the year 1666 (at which time I applied myself to the grinding of optic glasses of other figures than spherical), I procured me a triangular prism, to try therewith the celebrated phenomena of colours. And in order thereto having darkened my chamber, and made a small hole in the window shuts to let in a convenient quantity of the sun's light, I placed my prism at its entrance, that it might thereby be refracted to the opposite wall."

"It was at first a very pleasing divertisment to view the vivid and intense colours produced thereby; but after a while, applying myself to consider them more circumspectly, I became surprised to see them in an oblong form, which, according to the received laws of refraction I expected should have been circular."

Newton then describes his crucial experiment. In this experiment, the beam of sunlight from the hole in the window shutters was refracted by two prisms in succession. The first prism spread the light into a rainbow-like band of colors. From this spectrum, he selected a beam of a single color, and allowed the beam to pass through a second prism; but when light of a single color passed through the second prism, the color did not change, nor was the image spread out into a band. No matter what Newton did to it, red light always remained red, once it had been completely separated from the other colors; yellow light remained yellow, green remained green, and blue remained blue.

Newton then measured the amounts by which the beams of various colors were bent by the second prism; and he discovered that red light was bent the least. Next in sequence came orange, yellow, green, blue and finally violet, which was deflected the most. Newton recombined the separated colors, and he found that together, they once again produced white light.

Concluding the description of his experiments, Newton wrote:

"...and so the true cause of the length of the image (formed by the first prism) was detected to be no other than that light is not similar or homogenial, but consists of *deform rays, some of which are more refrangible than others*."

"As rays of light differ in their degrees of refrangibility, so they also differ in their disposition to exhibit this or that particular colour... To the same degree of refrangibility ever belongs the same colour, and to the same colour ever belongs the same degree of refrangibility."

"...The species of colour and the degree of refrangibility belonging to any particular sort of rays is not mutable by refraction, nor by reflection from natural bodies, nor by any other cause that I could yet observe. When any one sort of rays hath been well parted from those of other kinds, it hath afterwards obstinately retained its colour, notwithstanding my utmost endeavours to change it."

During the plague years of 1665 and 1666, Newton also began the work which led to his great laws of motion and universal gravitation. Referring to the year 1666, he wrote:

"I began to think of gravity extending to the orb of the moon; and having found out how to estimate the force with which a globe revolving within a sphere presses the surface of the sphere, from Kepler's rule of the periodical times of the planets being in a sesquialternate proportion of their distances from the centres of their orbs, I deduced that the forces which keep the planets in their orbs must be reciprocally as the squares of the distances from the centres about which they revolve; and thereby compared the force requisite to keep the moon in her orb with the force of gravity at the surface of the earth, and found them to answer pretty nearly."

"All this was in the plague years of 1665 and 1666, for in those days I was in the prime of my age for invention, and minded mathematics and philosophy more than at any time since."

Galileo had studied the motion of projectiles, and Newton was able to build on this work by thinking of the moon as a sort of projectile, dropping towards the earth, but at the same time moving rapidly to the side. The combination of these two motions gives the moon its nearly-circular path.

From Kepler's third law, Newton had deduced that the force with which the sun attracts a planet must fall off as the square of the distance between the planet and the sun. With great boldness, he guessed that this force is *universal*, and that every object in the universe attracts every other object with a gravitational force which is directly proportional to the product of the two masses, and inversely proportional to the square of the distance between them.

Newton also guessed correctly that in attracting an object outside its surface, the earth acts as though its mass were concentrated at its center. However, he could not construct the proof of this theorem, since it depended on integral calculus, which did not exist in 1666. (Newton himself invented integral calculus later in his life.)

In spite of the missing proof, Newton continued and "...compared the force requisite to keep the moon in her orb with the force of gravity at the earth's surface, and found them to answer pretty nearly". He was not satisfied with this incomplete triumph, and he did not show his calculations to anyone. He not only kept his ideas on gravitation to himself, (probably because of the missing proof), but he also refrained for many years from publishing his work on the calculus. By the time Newton published, the calculus had been invented independently by the great German mathematician and philosopher, Gottfried Wilhelm Leibniz (1646-1716); and the result was a bitter quarrel over priority. However, Newton did publish his experiments in optics, and these alone were enough to make him famous.

In 1669, Newton's teacher, Isaac Barrow, generously resigned his post as Lucasian Professor of Mathematics so that Newton could have it. Thus, at the age of 27, Newton became the head of the mathematics department at Cambridge. He was required to give eight lectures a year, but the rest of his time was free for research.

Newton's prism experiments had led him to believe that the only possible way to avoid blurring of colors in the image formed by a telescope was to avoid refraction entirely. Therefore he designed and constructed the first reflecting telescope. In 1672, he presented a reflecting telescope to the newly-formed Royal Society, which then elected him to membership.

Meanwhile, the problems of gravitation and planetary motion were increasingly discussed by the members of the Royal Society. In January, 1684, three members of the Society were gathered in a London coffee house. One of them was Robert Hooke (1635-1703), author of *Micrographia* and Professor of Geometry at Gresham College, a brilliant but irritable man. He had begun his career as Robert Boyle's assistant, and had gone on to do important work in many fields of science. Hooke claimed that he could calculate the motion of the planets by assuming that they were attracted to the sun by a force which diminished as the square of the distance.

Listening to Hooke were Sir Christopher Wren (1632-1723), the designer of St. Paul's Cathedral, and the young astronomer, Edmund Halley (1656-1742). Wren challenged Hooke to produce his calculations; and he offered to present Hooke with a book worth 40 shillings if he could prove his inverse square force law by means of rigorous mathematics. Hooke tried for several months, but he was unable to win Wren's reward.

Meanwhile, in August, 1684, Halley made a journey to Cambridge to talk with Newton, who was rumored to know very much more about the motions of the planets than he had revealed in his published papers. According to an almost-contemporary account, what happened then was the following:

"Without mentioning his own speculations, or those of Hooke and Wren, he (Halley) at once indicated the object of his visit by asking Newton what would be the curve described by the planets on the supposition that gravity diminished as the square of the distance. Newton immediately answered: an Ellipse. Struck with joy and amazement, Halley asked how he knew it? 'Why', replied he, 'I have calculated it'; and being asked for the calculation, he could not find it, but promised to send it to him."

Newton soon reconstructed the calculation and sent it to Halley; and Halley, filled with enthusiasm and admiration, urged Newton to write out in detail all of his work on motion and gravitation. Spurred on by Halley's encouragement and enthusiasm, Newton began to put his research in order. He returned to the problems which had occupied him during the plague years, and now his progress was rapid because he had invented integral calculus. This allowed him to prove rigorously that terrestrial gravitation acts as though all the earth's mass were concentrated at its center. Newton also had available an improved value for the radius of the earth, measured by the French astronomer Jean Picard (1620-1682). This time, when he approached the problem of gravitation, everything fell into place.

By the autumn of 1684, Newton was ready to give a series of lectures on dynamics, and he sent the notes for these lectures to Halley in the form of a small booklet entitled *On the Motion of Bodies*. Halley persuaded Newton to develop these notes into a larger book, and with great tact and patience he struggled to keep a controversy from developing between Newton, who was neurotically sensitive, and Hooke, who was claiming his share of recognition in very loud tones, hinting that Newton was guilty of plagiarism.

Newton reacted by striking out from his book every single reference to Robert Hooke. The Royal Society at first offered to pay for the publication costs of Newton's book, but because a fight between Newton and Hooke seemed possible, the Society discretely backed out. Halley then generously offered to pay the publication costs himself, and in 1686 Newton's great book was printed. It is entitled *Philosophae Naturalis Principia Mathematica*, (The Mathematical Principles of Natural Philosophy), and it is divided into three sections.

The first book sets down the general principles of mechanics. In it, Newton states his three laws of motion, and he also discusses differential and integral calculus (both invented by himself).

In the second book, Newton applies these methods to systems of particles and to hydrodynamics. For example, he calculates the velocity of sound in air from the compressibility

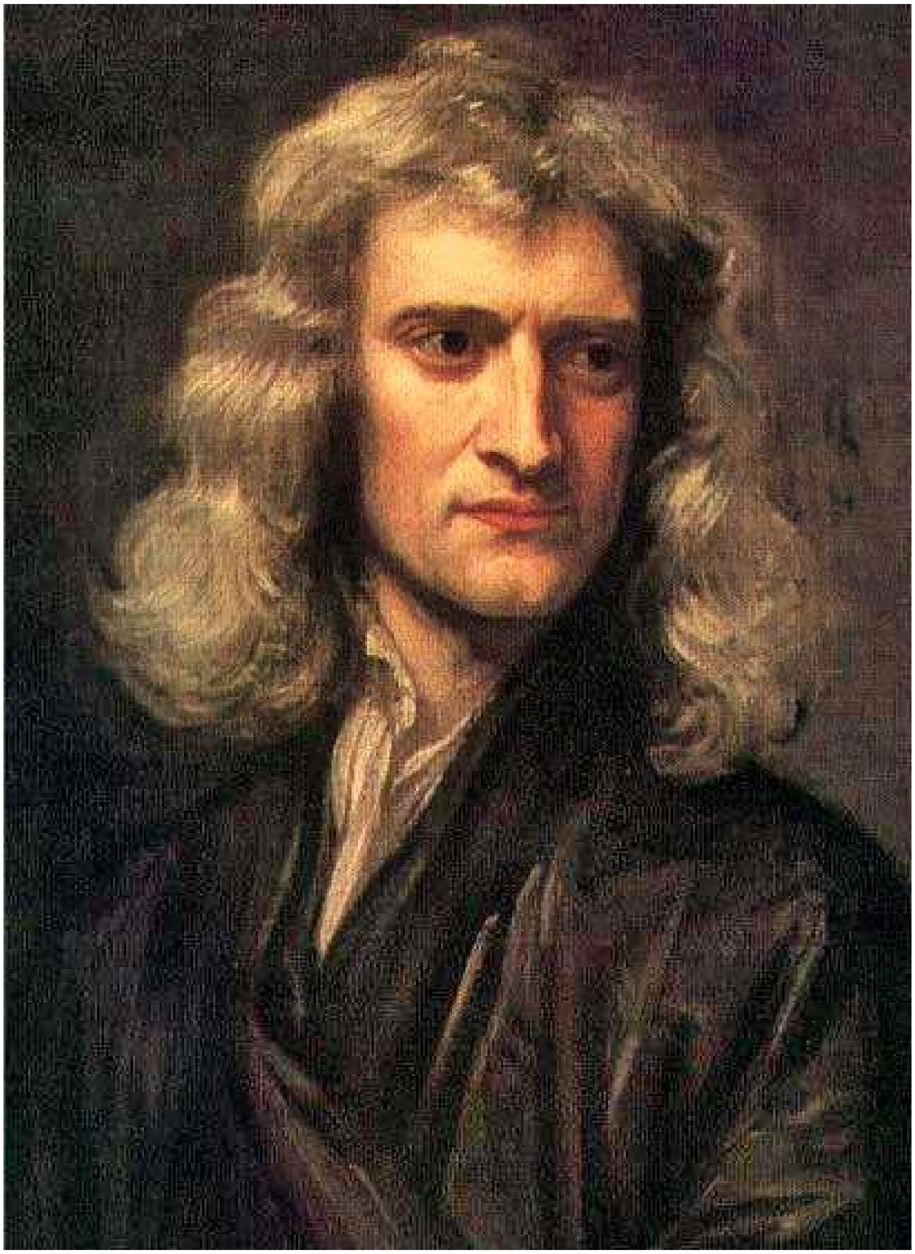

Figure 3.1: **Sir Isaac Newton (1642-1726) achieved a great synthesis, uniting the work of Copernicus, Brahe, Kepler and Galileo. Referring to these predecessors, Newton said, “If I have seen farther than other men, it is because I have stood on the shoulders of giants”.**

and density of air; and he treats a great variety of other problems, such as the problem of calculating how a body moves when its motion is slowed by a resisting medium, such as air or water.

The third book is entitled *The System of the World.* In this book, Newton sets out to derive the entire behavior of the solar system from his three laws of motion and from his law of universal gravitation. From these, he not only derives all three of Kepler's laws, but he also calculates the periods of the planets and the periods of their moons; and he explains such details as the flattened, non-spherical shape of the earth, and the slow precession of its axis about a fixed axis in space. Newton also calculated the irregular motion of the moon resulting from the combined attractions of the earth and the sun; and he determined the mass of the moon from the behavior of the tides.

Newton's *Principia* is generally considered to be one of the greatest scientific works of all time. To present a unified theory explaining such a wide variety of phenomena with so few assumptions was a magnificent and unprecedented achievement; and Newton's contemporaries immediately recognized the importance of what he had done.

The great Dutch physicist, Christian Huygens (1629-1695), inventor of the pendulum clock and the wave theory of light, travelled to England with the express purpose of meeting Newton. Voltaire, who for reasons of personal safety was forced to spend three years in England, used the time to study Newton's *Principia*; and when he returned to France, he persuaded his mistress, Madame du Chatelet, to translate the *Principia* into French; and Alexander Pope, expressing the general opinion of his contemporaries, wrote a famous couplet, which he hoped would be carved on Newton's tombstone:

"Nature and Nature's law lay hid in night.

God said: 'Let Newton be!', and all was light!"

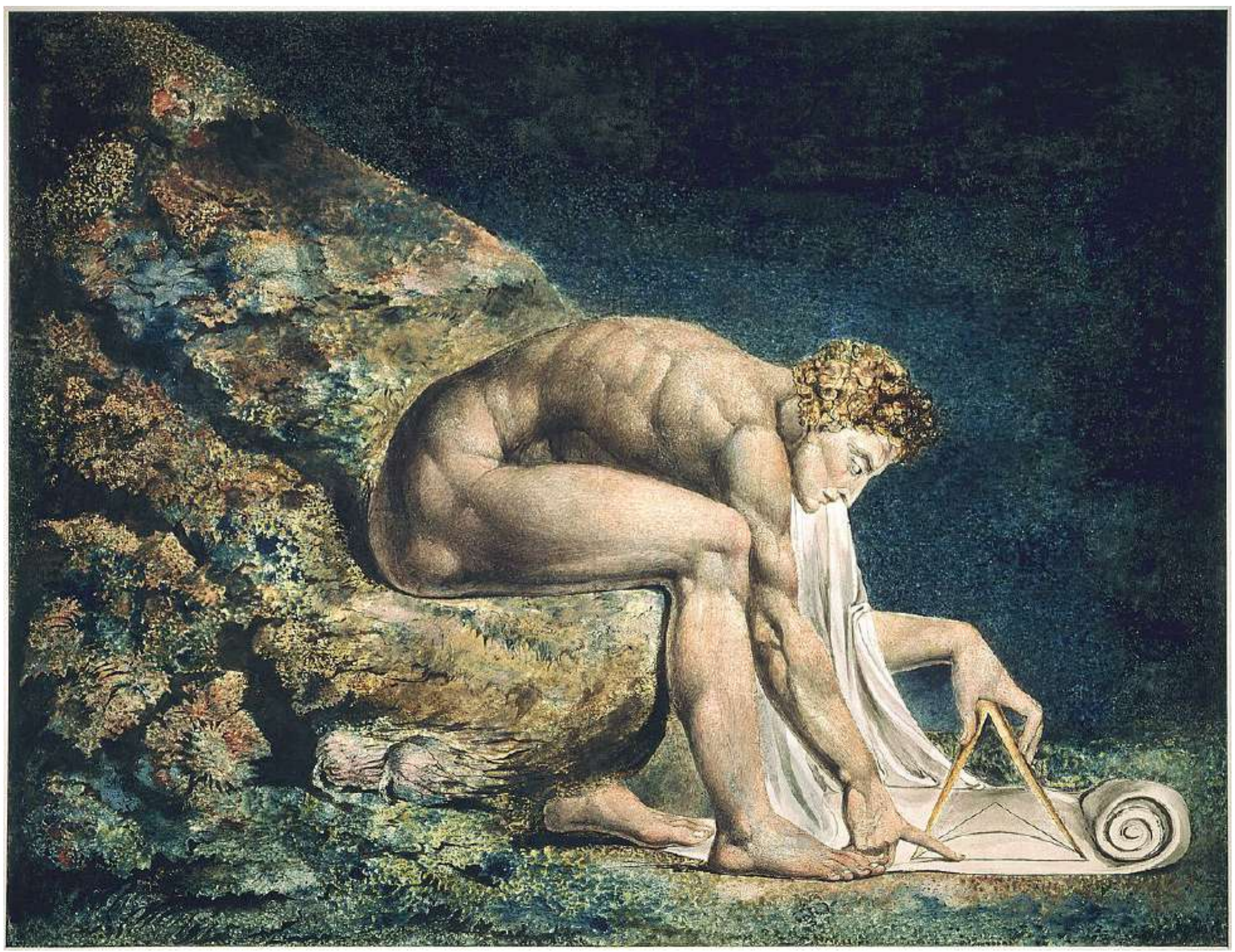

Figure 3.2: **Newton depicted in a print by William Blake.**

Figure 3.3: **The frontpiece of Voltaire's book popularizing Newton's ideas for French readers. His mistress, Madame du Châtelet appears as a muse, reflecting Newton's thoughts down to Voltaire.**

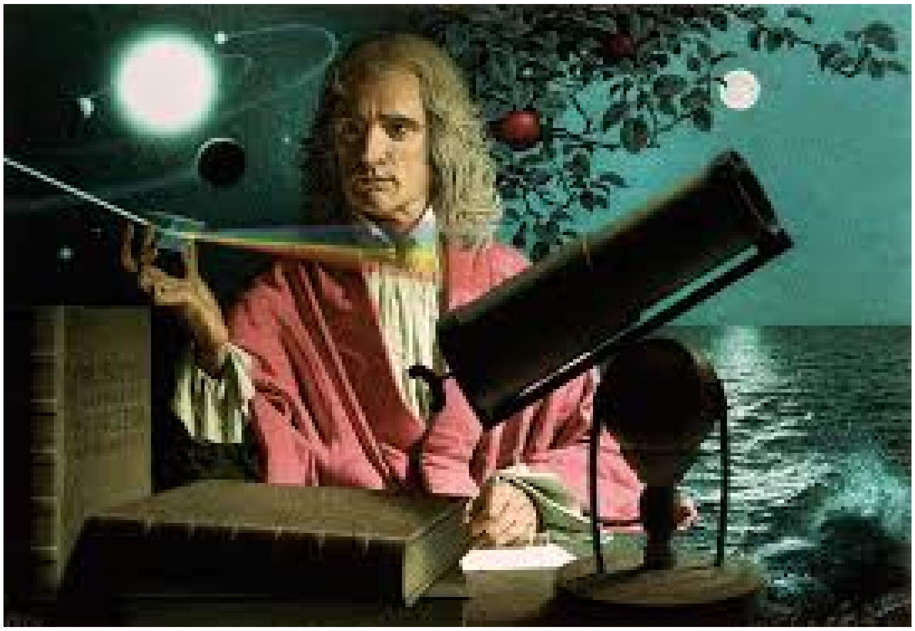

Figure 3.4: **Newton: "I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."**

Figure 3.5: **A statue of Newton at Trinity College, Cambridge. "...with his prism and his silent face, the marble index of a mind forever voyaging through strange seas of thought, alone."**

3.2 Lagrange and Laplace

Joseph-Louis Lagrange (1736-1824) and Pierre-Simon Laplace (1749-1827) both contributes importantly to the development of celestial mechanics in France during the Napoleonic era. Lagrange, the elder of the two, was born in Italy, but spent twenty years as director of mathematics at the Prussian Academy of Sciences. Lagrange's two-volume book on analytical mechanics was published on Paris by Gauthier-Villars et fils in 1788 and 1789. It was the most comprehensive treatment of classical mechanics since Newton, and it formed the basis of much of physics during the 19th century. In 1787 Lagrange moved to Paris, where he became a member of the French Academy of Sciences, and later a Senator.

Pierre-Simon Laplace (1749-1827) was a mathematical genius, sometimes referred to as "The French Newton", and remembered as one of the greatest mathematical physicists of all time. His natural ability was unmatched by any of his contemporaries. Although born in the provincial town of Beaumont-en-Auge, Normandy, the youthful Laplace was soon corresponding with such luminaries as Lagrange and d'Alembert.

Later, in Paris, the prestige of Laplace was so high that Napoleon found it useful to appoint him as Minister of the Interior. However, the appointment was only a brief one, and Laplace returned to his scholarly problems. During the years 1799-1825, he published his important five-volume work, *Mécanique Céleste* (Celestial Mechanics).

Interestingly Laplace postulated the existence of black holes.

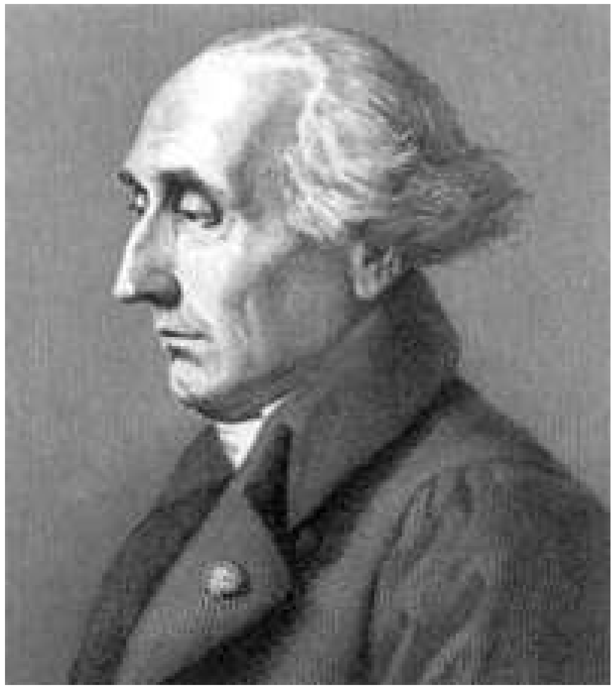

Figure 3.6: **Count Joseph-Louis Lagrange (1736-1824).**

Figure 3.7: **Pierre-Simon Laplace (1749-1827) as Chancellor of the Senate under the First French Empire. He was later made a Marquis by the Bourbons.**

Figure 3.8: **Sir William Rowan Hamilton (1805-1865).**

Figure 3.9: **Irish commemorative coin celebrating the 200th Anniversary of Hamilton's birth.**

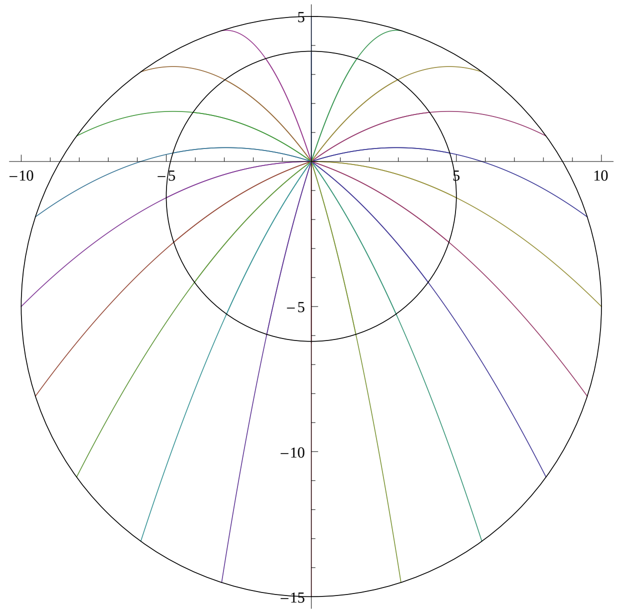

Figure 3.10: **This figure shows a system of particle trajectories of the kind visualized by Hamilton. Here the system might be produced by the fragments of an exploding sky-rocket, assuming that they are all of equal mass and are thrown out with equal velocities. At various times after the explosion, the fragments will reach points given by spheres drawn around the falling center of mass.**

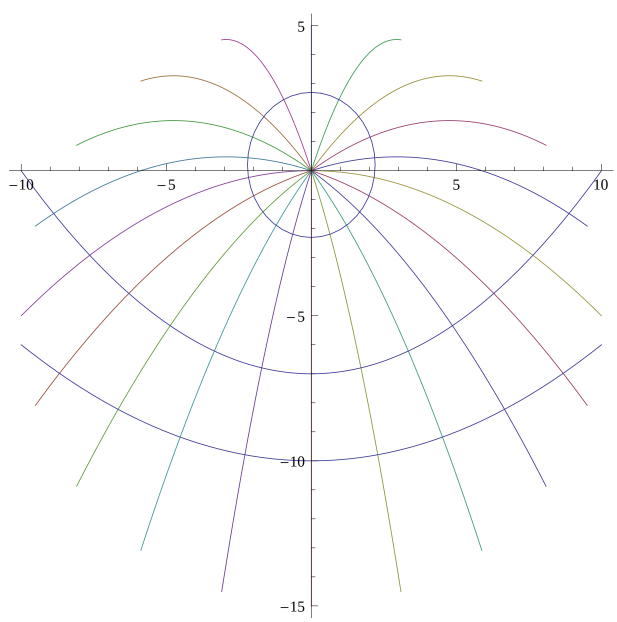

Figure 3.11: **This figure shows surfaces corresponding to constant values of Hamilton's characteristic function S. These surfaces are everywhere perpendicular to the trajectories discussed in the previous figure.**

3.3 Hamilton

Sir William Rowan Hamilton (1805-1865) made many extremely important contributions both to mathematics and to physics. He was a remarkable child prodigy. At the age of three, he was given to his uncle, James Hamilton, to be educated. His uncle was a linguist, and by the time William was thirteen years old, he had acquired as many languages as he had years of age. Besides all the classical and modern European languages, these included Persian, Arabic, Hindustani, Sanskrit, and even Marathi and Malay. In those days, Hamilton slept in a room next to his uncle with a string tied to the back of his nightshirt. The string went through a hole in the wall to his uncle's room. When the uncle thought that it was time for his nephew to wake up and work, he pulled the string.

Hamilton retained his knowledge of languages until the end of his life, and often read books in Persian and Arabic for pleasure. Fortunately, however, this orgy of linguistics was not continued and Hamilton became strongly interested in mathematics. At the age of 18, he submitted a *Memoir on Systems of Rays* for publication. It caused the Astronomer Royal of Ireland to exclaim, "This young man, I do not say *will be* but *is* the first mathematician of his age!"

With remarkable intuition, Hamilton anticipated both quantum theory and the general theory of relativity. He saw the close analogy between geometrical optics and the classical trajectories of Newtonian mechanics. In geometrical optics, the rays of light are perpendicular to wave fronts. Hamilton introduced a function that yielded wave fronts for mechanics, thus anticipating wave mechanics, a field that lay a century ahead in time. His reformulation of Newtonian mechanics also anticipated general relativity by showing that the trajectories of objects can be viewed as the shortest paths in a space with a special metric. The Hamiltonian reformulation of Newtonian mechanics has proved to be the a key to the development of modern physics.

Hamilton entered Trinity College, Dublin, where his scholastic record was remarkable. At the age of 21, while still an undergraduate, he was appointed to be Andrews Professor of Astronomy and Royal Astronomer of Ireland. He then moved into Dunsink Observatory, where he spent the remainder of his life. He married a clergyman's daughter, and they had three children together, but she could not stand the strain of living with him and returned to live with her parents.

Hamilton was the close friend of the poets Coleridge and Wordsworth, and his life had a profligate poetic quality. His lectures on astronomy attracted many scholars and poets, and even ladies, which at that time was unusual. One of his lectures inspired the poet Felicia Hermans to write *The Prayer of a Lonely Student*.

Hamilton drank a great deal, and the heaps of papers in his study were in a state of disorder. During the last part of his life, he was often alone, cared for by the house-keeper of the observatory. He had no regular meals, but from time to time, the house-keeper would hand him a mutton chop, which he would accept without a word, and without looking up from his work. After Hamilton's death, dozens of partly-eaten mutton chops were found among his mounds of papers.

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Chapter 4

HUYGENS, RØMER AND MAXWELL

4.1 Christiaan Huygens: The wave theory of light

Newton's rejection of the wave theory

Strangely, Sir Isaac Newton never accepted the wave theory of light, although he discussed the colors produced when a convex lens is placed on a flat piece of glass (Newton's rings) and the colors in soap bubbles and thin films of oil on water, phenomena that are most easily explained by the wave theory. He was also aware of Grimaldi's studies of the diffraction of light. In his old age, Newton may have doubted the correctness of his refusal to accept the wave theory, since his neighbors observed him spending many hours on his doorstep studying the colors exhibited by soap bubbles.

Huygens' early life and education

Christiaan Huygens (1629-1695) was born into a wealthy and influential Dutch family. His father, Constantijn Huygens, was a diplomat and advisor to the House of Orange which ruled Holland at the time. Christiaan Huygens was initially educated at home by private tutors, Later he studied law and mathematics at the University of Leiden and at the newly-founded Orange College in Breda. After completing his studies, Huygens served for some years as a diplomat. However, his career as a diplomat ended when the House of Orange fell form power. Huygens then returned to his father's houses in The Hague and in Hofwijck, where he devoted himself to scientific research. He made many important contributions, both to pure mathematics and to physics and probability theory, and he is remembered particularly for his invention of the pendulum clock, and his wave theory of light. As an astronomer, Huygens is noted for his improvements to refracting telescopes, and for his studies of the rings of Saturn and the discovery of its moon, Titan.

Figure 4.1: **Francesco Maria Grimaldi (1618-1663). He was an Italian priest, physicist and astronomer, who measured the height of the mountains on the moon. In physics, Grimaldi confirmed that freely falling bodies pass through a distance that is proportional to the square of the time. Grimaldi was the first to accurately describe the diffraction of light, a key confirmation of its wave nature.**

Figure 4.2: **Christiaan Huygens (1629-1695) by Caspar Netscher, Museum Boerhaave, Leiden.**

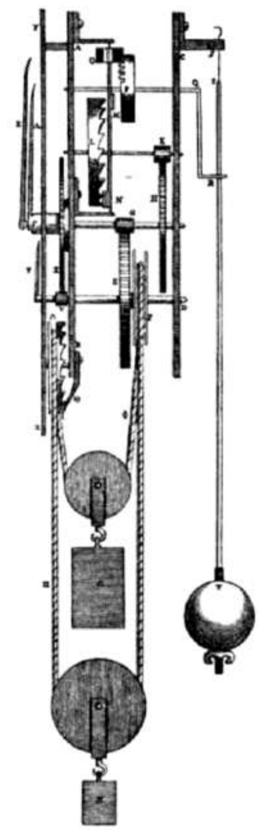

Figure 4.3: **The first pendulum clock, invented by Christiaan Huygens in 1656.**

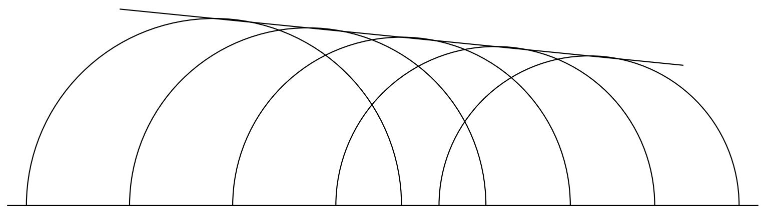

Figure 4.4: **This figure illustrates Huygens' Principle. Wavelets propagating outward from the old wave front with velocities appropriate to their positions collectively form the new wave front. Huygens was able to show that his principle led to the Snell-Descartes laws of refraction.**

Huygens' Principle

Christiaan Huygens proposed a principle, according to which each point on a wave front can be regarded as the source of a small circular wavelet propagating outward with a velocity characteristic of that point. The new wave front, an instant later, can be regarded as the sum of the contributions of all the small wavelets. In 1821, Augustin-Jean Fresnel (1788-1827) was able to demonstrate that Huygens' Principle can be used to explain the observed phenomena of diffraction. It then became known as the Huygens-Frenel Principle. Other experiments confirming Huygens' wave theory of light were performed by Thomas Young in 1803.

4.2 Ole Rømer: The velocity of light

The universally talented Danish astronomer Ole Rømer was born in Århus in 1644. Besides making the first measurement of the speed of light, he also invented the modern thermometer (later improved by Ferinheit), acted as police chief for Copenhagen, and introduced piped water and an improved sewage system for the city. In France, he was employed by Louis XIV to tutor the Dauphin, and he helped to design the spectacular fountains of Versailles. It was in France that Rømer made his famous measurement of the velocity of light. At that time, there was an urgent need for a method of determining longitude for long ocean voyages. Huygens had invented the pendulum clock, but because of the rocking of ships it was unsuitable for use on ocean voyages. Therefore it was thought that observation of astronomical events could provide a cosmic clock that could be used in navigation. As part of this effort, Ole Rømer and the Italian astronomer Cassini began to record the timing of the disappearance of a moon of Jupiter behind the planet, and its reappearance on the other side. Rømer noticed that the period of this cycle was longer when Saturn was receding from the Earth, and shorter when the two planets were approaching each other. Cassini dismissed this as an experimental error, but Rømer persisted in his careful measurements, finally deducing from them an astonishingly accurate value for the speed of light.

Figure 4.5: **A statue of the great Danish astronomer Ole Rømer on a hilltop to the west of Copenhagen. To the left are the few remains of his observatory. All that is left are the three pillars that supported his telescope. This hilltop can be reached from my own house on the outskirts of Copenhagen by cycling through the forest for 5 kilometers. Near to the site where the observatory once stood is Ole Rømer's Museum. with a large collection of early astronomical instruments. I remember visiting the museum with my family at a time when Halley's Comet was in the sky. We were allowed to look at the comet through one of the old telescopes.**

Figure 4.6: **A portrait of Ole Rømer (1644-1710). He made the first measurement of the speed of light by comparing the periods of the moons of Jupiter when the planet was moving towards the earth with the periods when it was receding. The value he obtained was astonishingly accurate.**

4.3 James Clerk Maxwell: Light as electromagnetic waves

Maxwell and Hertz

Michael Faraday had no mathematical training, but he made up for this lack with his powerful physical intuition. He visualized electric and magnetic fields as "lines of force" in the space around the wires, magnets and electrical condensers with which he worked. In the case of magnetic fields, he could even make the lines of force visible by covering a piece of cardboard with iron filings, holding it near a magnet, and tapping the cardboard until the iron filings formed themselves into lines along the magnetic lines of force.

In this way, Faraday could actually see the magnetic field running from the north pole of a magnet, out into the surrounding space, and back into the south pole. He could also see the lines of the magnetic field forming circles around a straight current-carrying wire. Similarly, Faraday visualized the lines of force of the electric field as beginning at the positive charges of the system, running through the intervening space, and ending at the negative charges.

Meanwhile, the German physicists (especially the great mathematician and physicist, Johann Karl Friedrich Gauss (1777-1855)), had utilized the similarity between Coulomb's law of electrostatic force and Newton's law of gravitation. Coulomb's law states that the force between two point charges varies as the inverse square of the distance between them - in other words, it depends on distance in exactly the same way as the gravitational force. This allowed Gauss and the other German mathematicians to take over the whole "action at a distance" formalism of theoretical astronomy, and to apply it to electrostatics.

Faraday was unhappy with the idea of action at a distance, and he expressed his feelings to James Clerk Maxwell (1831-1879), a brilliant young mathematician from Edinburgh who had come to visit him. The young Scottish mathematical genius was able to show Faraday that his idea of lines of force did not in any way contradict the German conception of action at a distance. In fact, when put into mathematical form, Faraday's picture of lines of force fit beautifully with the ideas of Gauss.

During the nine years from 1864 to 1873, Maxwell worked on the problem of putting Faraday's laws of electricity and magnetism into mathematical form. In 1873, he published *A Treatise on Electricity and Magnetism*, one of the truly great scientific classics. Maxwell achieved a magnificent synthesis by expressing in a few simple equations the laws governing electricity and magnetism in all its forms. His electromagnetic equations have withstood the test of time; and now, a century later, they are considered to be among the most fundamental laws of physics.

Maxwell's equations not only showed that visible light is indeed and electromagnetic wave, as Faraday had suspected, but they also predicted the existence of many kinds of invisible electromagnetic waves, both higher and lower in frequency than visible light. We now know that the spectrum of electromagnetic radiation includes (starting at the low-frequency end) radio waves, microwaves, infra-red radiation, visible light, ultraviolet rays,

Figure 4.7: **James Clerk Maxwell (1831-1879). When he put Faraday's experimental observations into mathematical form, Maxwell's equations predicted the existence of radio waves, and these were soon discovered by Heinrich Hertz.**

X-rays and gamma rays. All these types of radiation are fundamentally the same, except that their frequencies and wave lengths cover a vast range. They all are oscillations of the electromagnetic field; they all travel with the speed of light; and they all are described by Maxwell's equations.

Maxwell's book opened the way for a whole new category of inventions, which have had a tremendous impact on society. However, when the *Treatise on Electricity and Magnetism* was published, very few scientists could understand it. Part of the problem was that the scientists of the 19th century would have liked a mechanical explanation of electromagnetism.

Even Maxwell himself, in building up his ideas, made use of mechanical models, "..replete with ropes passing over pulleys, rolled over drums, pulling weights, or at times comprising tubes pumping water into other elastic tubes which expanded and contracted, the whole mass of machinery noisy with the grinding of interlocked gear wheels". In the end, however, Maxwell abandoned as unsatisfactory the whole clumsy mechanical scaffolding which he had used to help his intuition; and there is no trace of mechanical ideas in his final equations. As Synge has expressed it, "The robust body of the Cheshire cat was gone, leaving in its place only a sort of mathematical grin".

Lord Kelvin (1824-1907), a prominent English physicist of the time, was greatly disappointed because Maxwell's theory could offer no mechanical explanation for electromagnetism; and he called the theory "a failure - the hiding of ignorance under the cover of a formula". In Germany, the eminent physicist, Hermann von Helmholtz (1821-1894), tried hard to understand Maxwell's theory in mechanical terms, and ended by accepting Maxwell's equations without ever feeling that he really understood them.

In 1883, the struggles of von Helmholtz to understand Maxwell's theory produced a dramatic proof of its correctness: Helmholtz had a brilliant student named Heinrich Hertz (1857-1894), whom he regarded almost as a son. In 1883, the Berlin Academy of Science offered a prize for work in the field of electromagnetism; and von Helmholtz suggested to Hertz that he should try to win the prize by testing some of the predictions of Maxwell's theory.

Hertz set up a circuit in which a very rapidly oscillating electrical current passed across a spark gap. He discovered that electromagnetic waves were indeed produced by this rapidly-oscillating current, as predicted by Maxwell! The waves could be detected with a small ring of wire in which there was a gap. As Hertz moved about the darkened room with his detector ring, he could see a spark flashing across the gap, showing the presence of electromagnetic waves, and showing them to behave exactly as predicted by Maxwell.

The waves detected by Hertz were, in fact, radio waves; and it was not long before the Italian engineer, Guglielmo Marconi (1874-1937), turned the discovery into a practical means of communication. In 1898, Marconi used radio signals to report the results of the boat races at the Kingston Regatta, and on December 12, 1901, using balloons to lift the antennae as high as possible, he sent a signal across the Atlantic Ocean from England to Newfoundland.

In 1904, a demonstration of a voice-carrying radio apparatus developed by Fessenden was the sensation of the St. Louis World's Fair; and in 1909, Marconi received the Nobel

Prize in physics for his development of radio communications. In America, the inventive genius of Alexander Graham Bell (1847-1922) and Thomas Alva Edison (1847-1931) turned the discoveries of Faraday and Maxwell into the telephone, the electric light, the cinema and the phonograph.

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Chapter 5

EINSTEIN

5.1 Family background

Albert Einstein was born in Ulm, Germany, in 1879. He was the son of middle-class, irreligious Jewish parents, who sent him to a Catholic school. Einstein was slow in learning to speak, and at first his parents feared that he might be retarded; but by the time he was eight, his grandfather could say in a letter: "Dear Albert has been back in school for a week. I just love that boy, because you cannot imagine how good and intelligent he has become."

Remembering his boyhood, Einstein himself later wrote: "When I was 12, a little book dealing with Euclidean plane geometry came into my hands at the beginning of the school year. Here were assertions, as for example the intersection of the altitudes of a triangle in one point, which, though by no means self-evident, could nevertheless be proved with such certainty that any doubt appeared to be out of the question. The lucidity and certainty made an indescribable impression on me."

When Albert Einstein was in his teens, the factory owned by his father and uncle began to encounter hard times. The two Einstein families moved to Italy, leaving Albert alone and miserable in Munich, where he was supposed to finish his course at the gymnasium. Einstein's classmates had given him the nickname "Beidermeier", which means something like "Honest John"; and his tactlessness in criticizing authority soon got him into trouble. In Einstein's words, what happened next was the following: "When I was in the seventh grade at the Lutpold Gymnasium, I was summoned by my home-room teacher, who expressed the wish that I leave the school. To my remark that I had done nothing wrong, he replied only, 'Your mere presence spoils the respect of the class for me'."

Einstein left gymnasium without graduating, and followed his parents to Italy, where he spent a joyous and carefree year. He also decided to change his citizenship. "The over-emphasized military mentality of the German State was alien to me, even as a boy", Einstein wrote later. "When my father moved to Italy, he took steps, at my request, to have me released from German citizenship, because I wanted to be a Swiss citizen."

Figure 5.1: **Albert Einstein at the age of three years. This is believed to be the oldest known photograph of Einstein.**

Figure 5.2: **Albert Einstein in 1893 (age 14).**

The financial circumstances of the Einstein family were now precarious, and it was clear that Albert would have to think seriously about a practical career. In 1896, he entered the famous Zürich Polytechnic Institute with the intention of becoming a teacher of mathematics and physics. However, his undisciplined and nonconformist attitudes again got him into trouble. His mathematics professor, Hermann Minkowski (1864-1909), considered Einstein to be a "lazy dog"; and his physics professor, Heinrich Weber, who originally had gone out of his way to help Einstein, said to him in anger and exasperation: "You're a clever fellow, but you have one fault: You won't let anyone tell you a thing! You won't let anyone tell you a thing!"

Einstein missed most of his classes, and read only the subjects which interested him. He was interested most of all in Maxwell's theory of electro-magnetism, a subject which was too "modern" for Weber. There were two major examinations at the Zürich Polytechnic Institute, and Einstein would certainly have failed them had it not been for the help of his loyal friend, the mathematician Marcel Grossman.

Grossman was an excellent and conscientious student, who attended every class and took meticulous notes. With the help of these notes, Einstein managed to pass his examinations; but because he had alienated Weber and the other professors who could have helped him, he found himself completely unable to get a job. In a letter to Professor F. Ostwald on behalf of his son, Einstein's father wrote: "My son is profoundly unhappy because of his present joblessness; and every day the idea becomes more firmly implanted

Figure 5.3: **Albert Einstein with Zürich friends Habicht and Solovine, ca. 1903. They met informally to discuss physics, calling themselves the "Olympia Academy".**

in his mind that he is a failure, and will not be able to find the way back again."

From this painful situation, Einstein was rescued (again!) by his friend Marcel Grossman, whose influential father obtained for Einstein a position at the Swiss Patent Office: Technical Expert (Third Class). Anchored at last in a safe, though humble, position, Einstein married one of his classmates. He learned to do his work at the Patent Office very efficiently; and he used the remainder of his time on his own calculations, hiding them guiltily in a drawer when footsteps approached.

In 1905, this Technical Expert (Third Class) astonished the world of science with five papers, written within a few weeks of each other, and published in the Annalen der Physik. Of these five papers, three were classics: One of these was the paper in which Einstein applied Planck's quantum hypothesis to the photoelectric effect. The second paper discussed "Brownian motion", the zig-zag motion of small particles suspended in a liquid and hit randomly by the molecules of the liquid. This paper supplied a direct proof of the validity of atomic ideas and of Boltzmann's kinetic theory. The third paper was destined to establish Einstein's reputation as one of the greatest physicists of all time. It was entitled "On the Electrodynamics of Moving Bodies", and in this paper, Albert Einstein formulated his special theory of relativity. Essentially, this theory maintained that all of the fundamental laws of nature exhibit a symmetry with respect to rotations in a 4-dimensional space-time continuum.

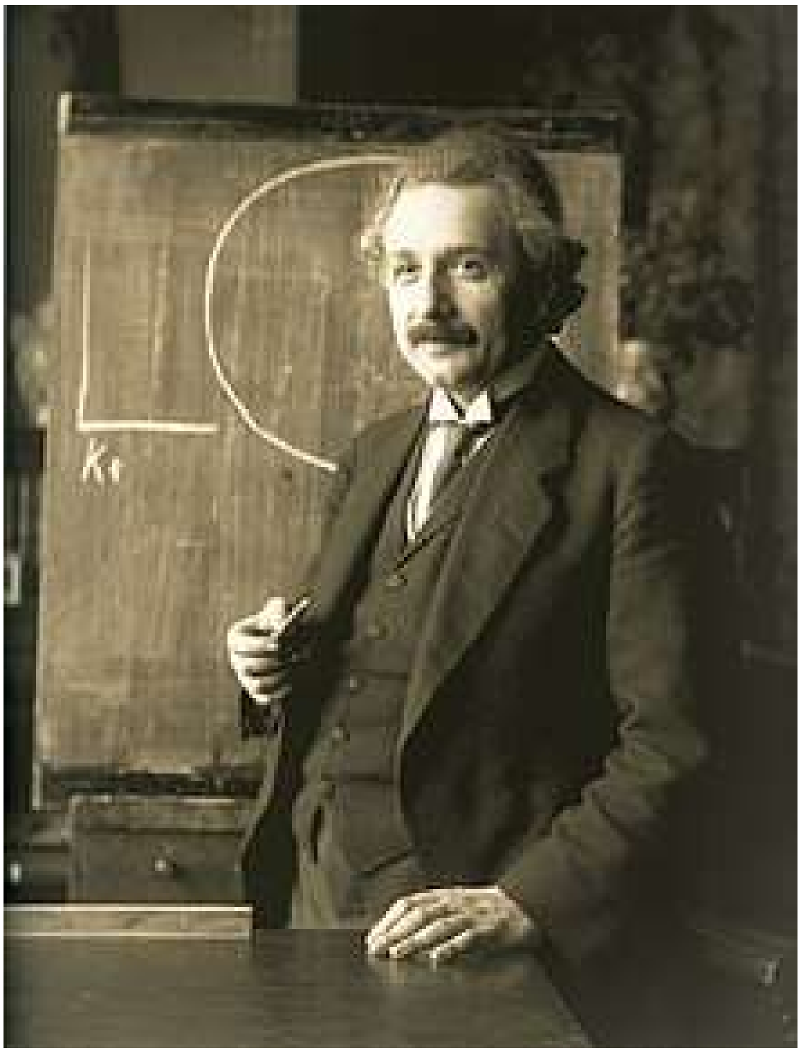

Figure 5.4: **Albert Einstein in 1921.**

5.2 Special relativity theory

The theory of relativity grew out of problems connected with Maxwell's electromagnetic theory of light. Ever since the wavelike nature of light had first been demonstrated, it had been supposed that there must be some medium to carry the light waves, just as there must be some medium (for example air) to carry sound waves. A word was even invented for the medium which was supposed to carry electromagnetic waves: It was called the "ether".

By analogy with sound, it was believed that the velocity of light would depend on the velocity of the observer relative to the "ether". However, all attempts to measure differences in the velocity of light in different directions had failed, including an especially sensitive experiment which was performed in America in 1887 by A.A. Michelson and E.W. Morley.

Even if the earth had, by a coincidence, been stationary with respect to the "ether" when Michelson and Morley first performed their experiment, they should have found an "ether wind" when they repeated their experiment half a year later, with the earth at the other side of its orbit. Strangely, the observed velocity of light seemed to be completely independent of the motion of the observer!

In his famous 1905 paper on relativity, Einstein made the negative result of the Michelson-Morley experiment the basis of a far-reaching principle: He asserted that no experiment whatever can tell us whether we are at rest or whether we are in a state of uniform motion. With this assumption, the Michelson-Morley experiment of course had to fail, and the measured velocity of light had to be independent of the motion of the observer.

Einstein's Principle of Special Relativity had other extremely important consequences: He soon saw that if his principle were to hold, then Newtonian mechanics would have to be modified. In fact, Einstein's Principle of Special Relativity required that *all* fundamental physical laws exhibit a symmetry between space and time. The three space dimensions, and a fourth dimension, ict, had to enter every fundamental physical law in a symmetrical way. (Here i is the square root of -1, c is the velocity of light, and t is time.)

When this symmetry requirement is fulfilled, a physical law is said to be "Lorentz-invariant" (in honor of the Dutch physicist H.A. Lorentz, who anticipated some of Einstein's ideas). Today, we would express Einstein's principle by saying that every fundamental physical law must be Lorentz-invariant (i.e. symmetrical in the space and time coordinates). The law will then be independent of the motion of the observer, provided that the observer is moving uniformly.

Einstein was able to show that, when properly expressed, Maxwell's equations are already Lorentz-invariant; but Newton's equations of motion have to be modified. When the needed modifications are made, Einstein found, then the mass of a moving particle appears to increase as it is accelerated. A particle can never be accelerated to a velocity greater than the velocity of light; it merely becomes heavier and heavier, the added energy being converted into mass.

From his 1905 theory, Einstein deduced his famous formula equating the energy of a system to its mass multiplied by the square of the velocity of light. As we shall see, his formula was soon used to explain the source of the energy produced by decaying uranium and radium; and eventually it led to the construction of the atomic bomb. Thus Einstein, a lifelong pacifist, who renounced his German citizenship as a protest against militarism, became instrumental in the construction of the most destructive weapon ever invented - a weapon which casts an ominous shadow over the future of humankind.

Just as Einstein was one of the first to take Planck's quantum hypothesis seriously, so Planck was one of the first physicists to take Einstein's relativity seriously. Another early enthusiast for relativity was Hermann Minkowski, Einstein's former professor of mathematics. Although he once had characterized Einstein as a "lazy dog", Minkowski now contributed importantly to the mathematical formalism of Einstein's theory; and in 1907, he published the first book on relativity. In honor of Minkowski's contributions to relativity, the 4-dimensional space-time continuum in which we live is sometimes called "Minkowski space".

In 1908, Minkowski began a lecture to the Eightieth Congress of German Scientists and Physicians with the following words:

" From now on, space by itself, and time by itself, are destined to sink completely into the shadows; and only a kind of union of both will retain an independent existence."

Gradually, the importance of Einstein's work began to be realized, and he was much sought after. He was first made Assistant Professor at the University of Zürich, then full Professor in Prague, then Professor at the Zürich Polytechnic Institute; and finally, in 1913, Planck and Nernst persuaded Einstein to become Director of Scientific Research at the Kaiser Wilhelm Institute in Berlin. He was at this post when the First World War broke out

While many other German intellectuals produced manifestos justifying Germany's invasion of Belgium, Einstein dared to write and sign an anti-war manifesto. Einstein's manifesto appealed for cooperation and understanding among the scholars of Europe for the sake of the future; and it proposed the eventual establishment of a League of Europeans. During the war, Einstein remained in Berlin, doing whatever he could for the cause of peace, burying himself unhappily in his work, and trying to forget the agony of Europe, whose civilization was dying in a rain of shells, machine-gun bullets, and poison gas.

5.3 General relativity

The work into which Einstein threw himself during this period was an extension of his theory of relativity. He already had modified Newton's equations of motion so that they exhibited the space-time symmetry required by his Principle of Special Relativity. However, Newton's law of gravitation. remained a problem.

Obviously it had to be modified, since it disagreed with his Special Theory of Relativity; but how should it be changed? What principles could Einstein use in his search for a more correct law of gravitation? Certainly whatever new law he found would have to give results very close to Newton's law, since Newton's theory could predict the motions of the planets with almost perfect accuracy. This was the deep problem with which he struggled.

In 1907, Einstein had found one of the principles which was to guide him, the Principle of Equivalence of inertial and gravitational mass. After turning Newton's theory over and over in his mind, Einstein realized that Newton had used mass in two distinct ways: His laws of motion stated that the force acting on a body is equal to the mass of the body multiplied by its acceleration; but according to Newton, the gravitational force on a body is also proportional to its mass. In Newton's theory, gravitational mass, by a coincidence, is equal to inertial mass; and this holds for all bodies. Einstein decided to construct a theory in which gravitational and inertial mass necessarily have to be the same.

He then imagined an experimenter inside a box, unable to see anything outside it. If the box is on the surface of the earth, the person inside it will feel the pull of the earth's gravitational field. If the experimenter drops an object, it will fall to the floor with an acceleration of 32 feet per second per second. Now suppose that the box is taken out into empty space, far away from strong gravitational fields, and accelerated by exactly 32 feet per second per second. Will the enclosed experimenter be able to tell the difference between these two situations? Certainly no difference can be detected by dropping an object, since in the accelerated box, the object will fall to the floor in exactly the same way as before.

With this "thought experiment" in mind, Einstein formulated a general Principle of Equivalence: He asserted that no experiment whatever can tell an observer enclosed in a small box whether the box is being accelerated, or whether it is in a gravitational field. According to this principle, gravitation and acceleration are locally equivalent, or, to say the same thing in different words, gravitational mass and inertial mass are equivalent.

Einstein soon realized that his Principle of Equivalence implied that a ray of light must be bent by a gravitational field. This conclusion followed because, to an observer in an accelerated frame, a light beam which would appear straight to a stationary observer, must necessarily appear very slightly curved. If the Principle of Equivalence held, then the same slight bending of the light ray would be observed by an experimenter in a stationary frame in a gravitational field.

Another consequence of the Principle of Equivalence was that a light wave propagating upwards in a gravitational field should be very slightly shifted to the red. This followed because in an accelerated frame, the wave crests would be slightly farther apart than they normally would be, and the same must then be true for a stationary frame in a gravitational field. It seemed to Einstein that it ought to be possible to test experimentally both the gravitational bending of a light ray and the gravitational red shift.

This seemed promising; but how was Einstein to proceed from the Principle of Equivalence to a formulation of the law of gravitation? Perhaps the theory ought to be modeled after Maxwell's electromagnetic theory, which was a field theory, rather than an "action at a distance" theory. Part of the trouble with Newton's law of gravitation was that it allowed a signal to be propagated instantaneously, contrary to the Principle of Special Relativity. A field theory of gravitation might cure this defect, but how was Einstein to find such a theory? There seemed to be no way.

From these troubles Albert Einstein was rescued (a third time!) by his staunch friend Marcel Grossman. By this time, Grossman had become a professor of mathematics in Zürich, after having written a doctoral dissertation on tensor analysis and non-Euclidean geometry, the very things that Einstein needed. The year was then 1912, and Einstein had

Figure 5.5: **The mathematician Marcel Grossmann (1878-1936), was Albert Einstein's staunch friend. He rescued Einstein a total of three times, at critical moments in Einstein's career.**

Figure 5.6: **Albert Einstein and his first wife, his classmate Mileva Maric.**

just returned to Zürich as Professor of Physics at the Polytechnic Institute. For two years, Einstein and Grossman worked together; and by the time Einstein left for Berlin in 1914, the way was clear. With Grossman's help, Einstein saw that the gravitational field could be expressed as a curvature of the 4-dimensional space-time continuum.

In 1919, a British expedition, headed by Sir Arthur Eddington, sailed to a small island off the coast of West Africa. Their purpose was to test Einstein's prediction of the bending of light in a gravitational field by observing stars close to the sun during a total eclipse. The observed bending agreed exactly with Einstein's predictions; and as a result he became world-famous. The general public was fascinated by relativity, in spite of the abstruseness of the theory (or perhaps because of it). Einstein, the absent-minded professor, with long, uncombed hair, became a symbol of science. The world was tired of war, and wanted something else to think about.

Einstein met President Harding, Winston Churchill and Charlie Chaplin; and he was invited to lunch by the Archbishop of Canterbury. Although adulated elsewhere, he was soon attacked in Germany. Many Germans, looking for an excuse for the defeat of their nation, blamed it on the pacifists and Jews; and Einstein was both these things.

5.4 Schwartzschild's solutions: Black holes

Here are some quotations from the Wikipedia article about Karl Schwarzschild:

"Schwarzschild provided the first exact solution to the Einstein field equations of general relativity, for the limited case of a single spherical non-rotating mass, which he accomplished in 1915, the same year that Einstein first introduced general relativity. The Schwarzschild solution, which makes use of Schwarzschild coordinates and the Schwarzschild metric, leads to a derivation

Figure 5.7: **The German physicist and astronomer Karl Schwartzschild (1873-1916). His work led him to the first exact solutions of Einstein's equations for general relativity. These solutions were limited to the case of non-rotating spherically symmetric systems, but they led him to predict the existence of black holes, and to give a value for their event-horizons. Kerl Schwartzschild was the father of Martin Schwartzschild, another very distinguished astrophysicist.**

of the Schwarzschild radius, which is the size of the event horizon of a non-rotating black hole...

"Thousands of dissertations, articles, and books have since been devoted to the study of Schwarzschild's solutions to the Einstein field equations. However, although Schwarzschild's best known work lies in the area of general relativity, his research interests were extremely broad, including work in celestial mechanics, observational stellar photometry, quantum mechanics, instrumental astronomy, stellar structure, stellar statistics, Halley's comet, and spectroscopy...

Karl Schwartzchild was born in Frankfurt am Main into a Jewish family whose roots in the city dated back to the 16th century. He was a child prodigy, and had two papers on celestial mechanics (on the motions of binary stars) published when he was only 15 years old. From 1901 to 1909, he was a professor at Göttingen's famous Mathematical Institute, where he had a chance to work with the pioneering mathematicians, Herman Minkowski and David Hilbert. Schwartzchild wrote his famous paper on the solutions to Eineteins equations while serving in the German army on the eastern front. He died there in 1916, not from wounds, but from a rare autoimmune disease called pemphigus.

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Chapter 6

LEVITT AND HUBBLE

6.1 Henrietta Swan Leavitt

Henrietta Swan Leavitt was born in 1868 into a long-established and prominent New England family. She was a descendant of Deacon John Leavitt (1608-1691), the founding Deacon of Old Ship Church in Plymouth County, Massachusetts, the oldest church in continuous ecclesiastical use in the United States. Her uncle, Erasmus Darwin Leavitt, was a famous mechanical engineer.

Henrietta first attended Oberlin University, but afterward transferred to Harvard University's Society for the Collegiate Instruction of Women (later renamed Radcliffe College), where she received a bachelor's degree in 1892. In addition to her classical courses, she studied analytic geometry, calculus and astronomy.

While at Radcliffe, Miss Leavitt began working at the Harvard College Observatory, measuring and recording the brightness of stars, as they appeared in the observatory's photographic collection. Since she was independently wealthy, she worked without asking for pay. Later she accepted a tiny, purely symbolic, amount of pay. In 1898 she joined the Harvard staff, as their first Curator of Astronomical Photographs.

In a 1912 paper, Henrietta Swan Leavitt communicated to the world's astronomers what later came to be known as Leavitt's Law. She examined 25 Cephiad variable stars in the Small Magellanic Cloud. These she assumed to be equidistant from the Earth. Therefore their apparent luminosity was proportional to their actual luminosity, the constant of proportionality being the same for all. Her studies showed that there is a simple relationship between the brightness of Cephiad variables and their periods: The logarithm of the period is proportional to the logarithm of the luminosity. She ended the paper by expressing the hope that the actual distance to the Small Magellanic Cloud would some day be measured by means of stellar parallax. This was later achieved, and Leavitt's Law became a hugely important tool for calibrating distances in the universe. Edwin Hubble, who used Leavitt's Law to show that the universe is almost unbelievably enormous and expanding, frequently said that Miss Leavitt deserved a Nobel Prize. Sadly, she died of cancer before this could happen.

Figure 6.1: **Henrietta Swan Leavitt (1868-1921).**

Figure 6.2: **Harvard College Observatory, Cambridge Massachusetts, circa 1899.**

Figure 6.3: **An increasingly deaf Henrietta Swan Leavitt working at her desk in the Harvard College Observatory.**

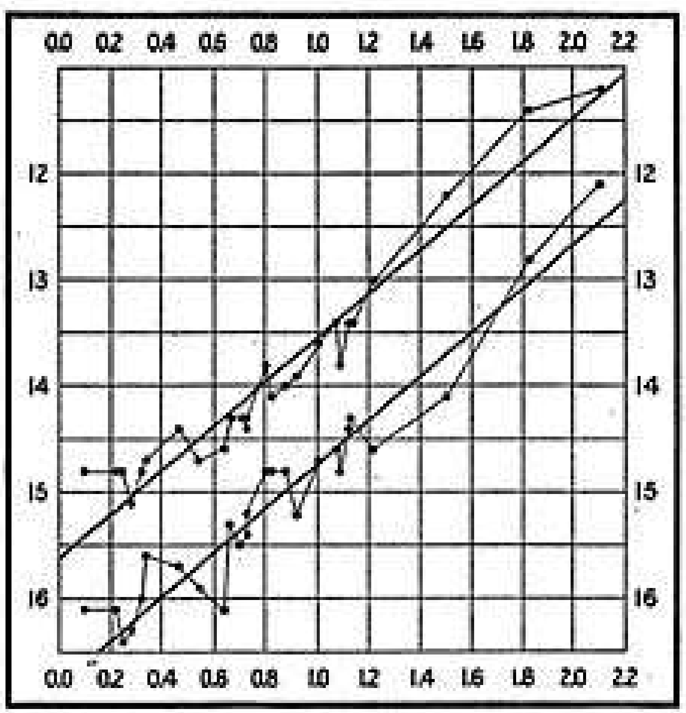

FIG. 2.

Figure 6.4: **Plot from a paper prepared by Leavitt in 1912. The horizontal axis is the logarithm of the period of the corresponding Cepheid, and the vertical axis is its magnitude. The lines drawn connect points corresponding to the stars' minimum and maximum brightness, respectively.**

6.2 Edwin Hubble

Edwin Hubble's father wanted him to become a lawyer, and following his father's dying request, he studied law, first at the University of Chicago, and then at Oxford University. However, his true passion was astronomy. During his Oxford law studies, he managed to take a number of science course. After the end of World War I, he became a student at Cambridge University, this time abandoning law and studying astronomy full-time.

In 1919, Hubble was offered a position at the Mount Wilson Observatory in Pasadena California, a position which he held until his death in 1953. Just as Hubble arrived, the Mount Wilson Observatory acquired the 100 inch Hooker telescope. At that time it was the world's largest, and it helped Hubble to make his important discoveries.

Hubble's special attention was drawn to the Cephiad variable stars, whose brightness varied with a characteristic period. A relationship between the period of Cephiad variable stars and their luminosity had been discovered in 1908 by Henrietta Swan Leavitt. Her discovery allowed astronomers to calculate the distance of a variable star by comparing its period with its apparent brightness. Using this relationship, Hubble was able to show that some of the variable stars which he could observe with the Hooker telescope were too far away to be part of our own galaxy. His studies of the Andromeda nebula, which had previously been thought to be a cloud of gas within our own galaxy, proved that it was in fact an entire galaxy very similar to our own Milky Way.

Edwin Hubble used the Doppler effect to make a second extremely important discovery. When a star is moving away from the earth, the light from the star is shifted to the red. In other words each color of light has a longer wave length than it would have if the star were stationary or moving towards us. This is similar to the effect that we can notice when the sound of the whistle of an approaching railway train falls in pitch as the train passes us and moves away. Hubble discovered that the red shift due to the Doppler effect is greatest for the galaxies that are farthest from the earth. This discovery, which is known as Hubble's Law, is interpreted by most astronomers as indicating that our universe as a whole is expanding.

In 1924, Edwin Hubble, who was then 35 years old, announced his epoch-making discoveries in the New York Times. In January, 1925, he followed this announcement with a formal paper, presented to a meeting of the American Astronomical Society.

Hubble's name is perhaps best known to the public because of the space telescope named after him. Why put a telescope into space? The reason is that for telescopes on even the highest of mountains, fluctuations in the density of air above them limits the resolution that they can achieve. Since the Hubble space telescope is completely above the earth's atmosphere, it has been able to send us remarkable images of our universe.

Figure 6.5: **Edwin Hubble (1889-1953).**

Figure 6.6: **The Andromeda spiral nebula.**

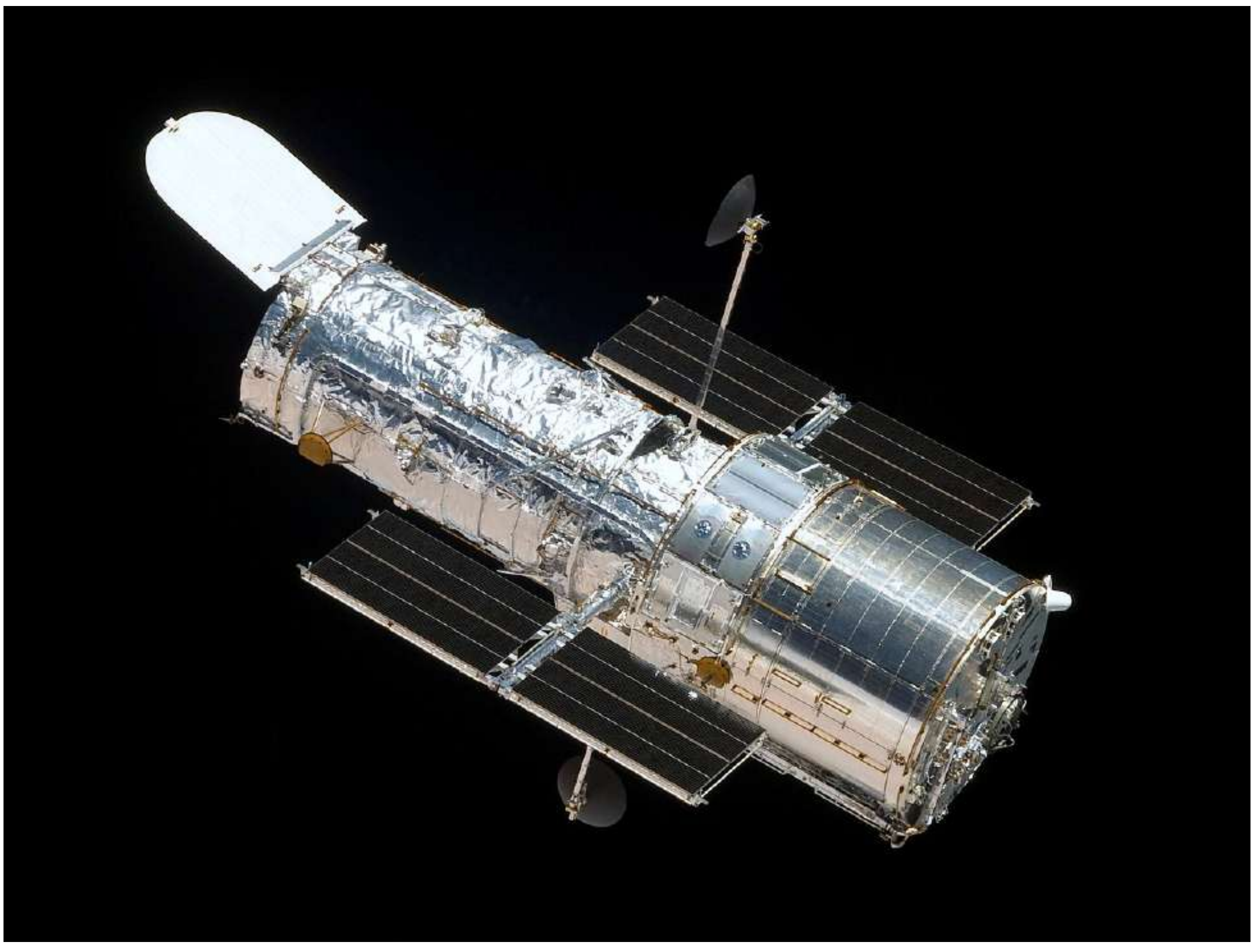

Figure 6.7: **The Hubble space telescope as seen by the departing Space Shuttle.**

Figure 6.8: **Edwin Hubble is regarded as one of the most important astronomers of all time.**

Figure 6.9: **The 100-inch Hooker telescope at Mount Wilson Observatory that Hubble used to measure galaxy distances and a value for the rate of expansion of the universe.**

6.3 The Hubble Space Telescope

The advantages of having a telescope orbiting the Earth rather than on the ground were obvious ever since the 1920's: The Earth's atmosphere absorbs frequencies of light in the ultraviolet and infra-red parts of the spectrum, besides which background light and the irregularity of the atmosphere limit the achievable resolution of terrestrial telescopes.

The Hubble Space Telescope (HST) was not the first telescope in space. However, it is the largest, most versatile and most important one. It was launched in 1990, after a long struggle in the US Congress over its budget. However, the astronomers who had struggled to achieve the launching were shocked when the first images transmitted back from HST were of extremely low quality. It turned out that there had been an error in grinding HST's glass mirror. After much thought, scientists invented a method for correcting the error. A Space Shuttle mission was sent to make the correction, and afterwards the HST returned superb images.

A few images from the HST

To celebrate the 23rd birthday of the Hubble Space Telescope, NASA released many striking photographs of the cosmos, a few of which are shown below.

Both Edwin Hubble himself, and the telescope named after him, have given humans a new view of the universe. The size of the universe is almost beyond comprehension. There are about a trillion galaxies in the observable universe! The number of stars in a galaxy varies, but assuming an average of 100 billion stars per galaxy means that there are about 100,000,000,000,000,000,000,000 (100 billion trillion) stars in the observable universe! In comparison, the Earth, although very important to us, seems insignificant.

Figure 6.10: **The cluster Westerlund 2 and its surroundings.**

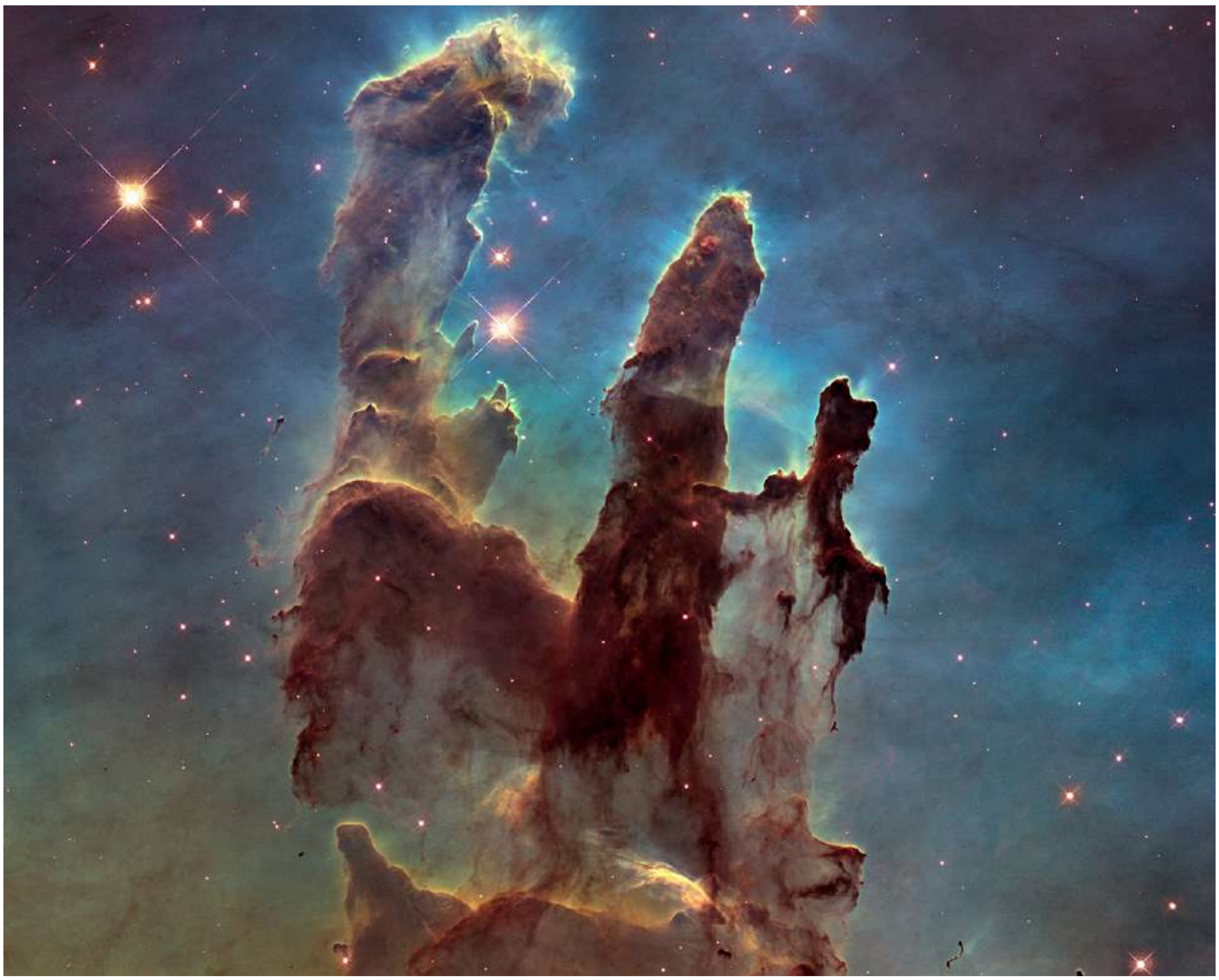

Figure 6.11: **The Eagle Nebula's Pillars of Creation.**

Figure 6.12: **A pair of interacting galaxies called Arp 273.**

Figure 6.13: **The star-forming region NGC 3603.**

Figure 6.14: **The Bubble Nebula, also known as NGC 7635, is an emission nebula located 8,000 light-years away.**

Figure 6.15: **The Antennae Galaxies.**

Figure 6.16: **A new infrared view of the Horsehead Galaxy.**

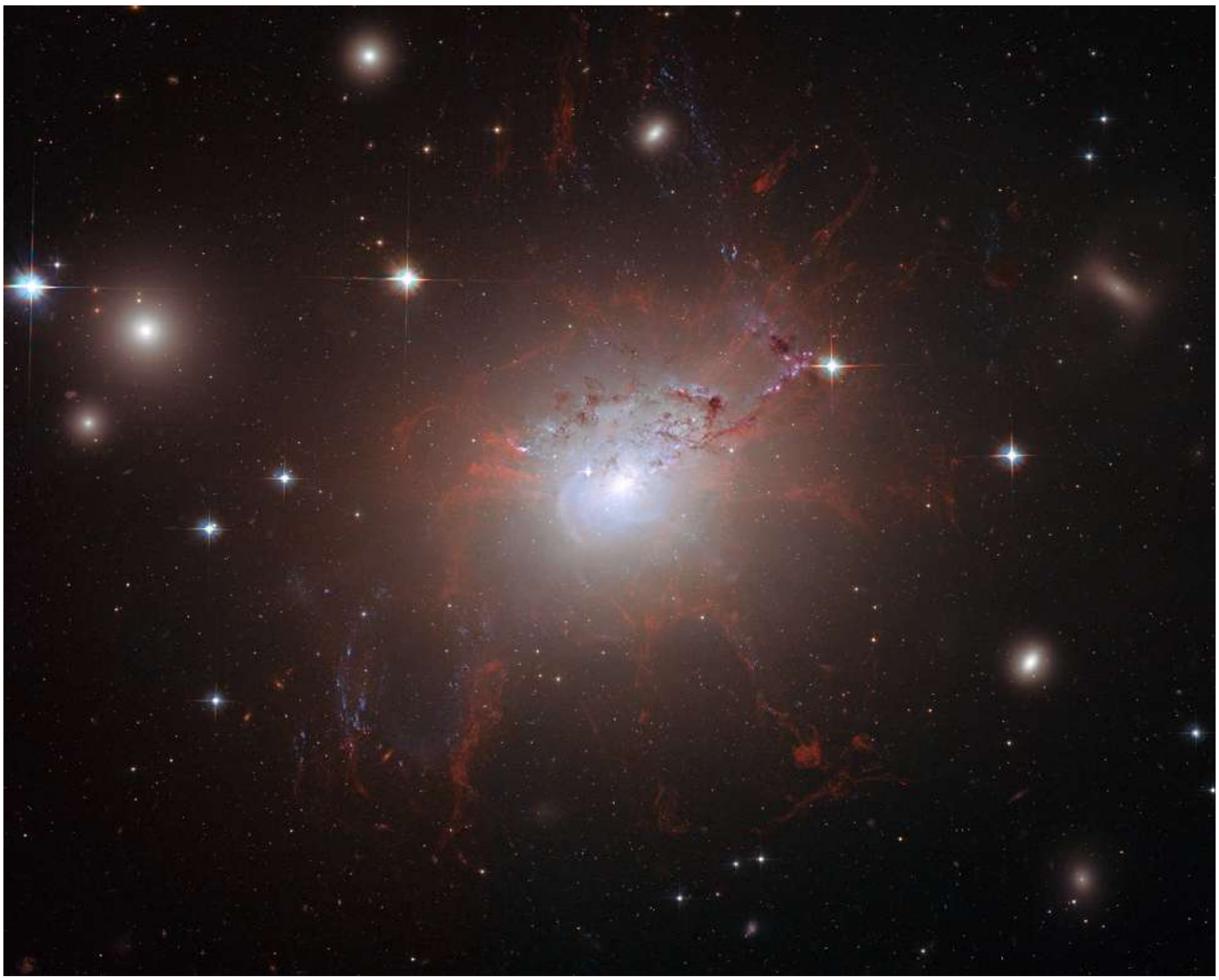

Figure 6.17: **The magnetic galaxy NGC 1275. Energy from the central black hole is transferred to the surriouding gas.**

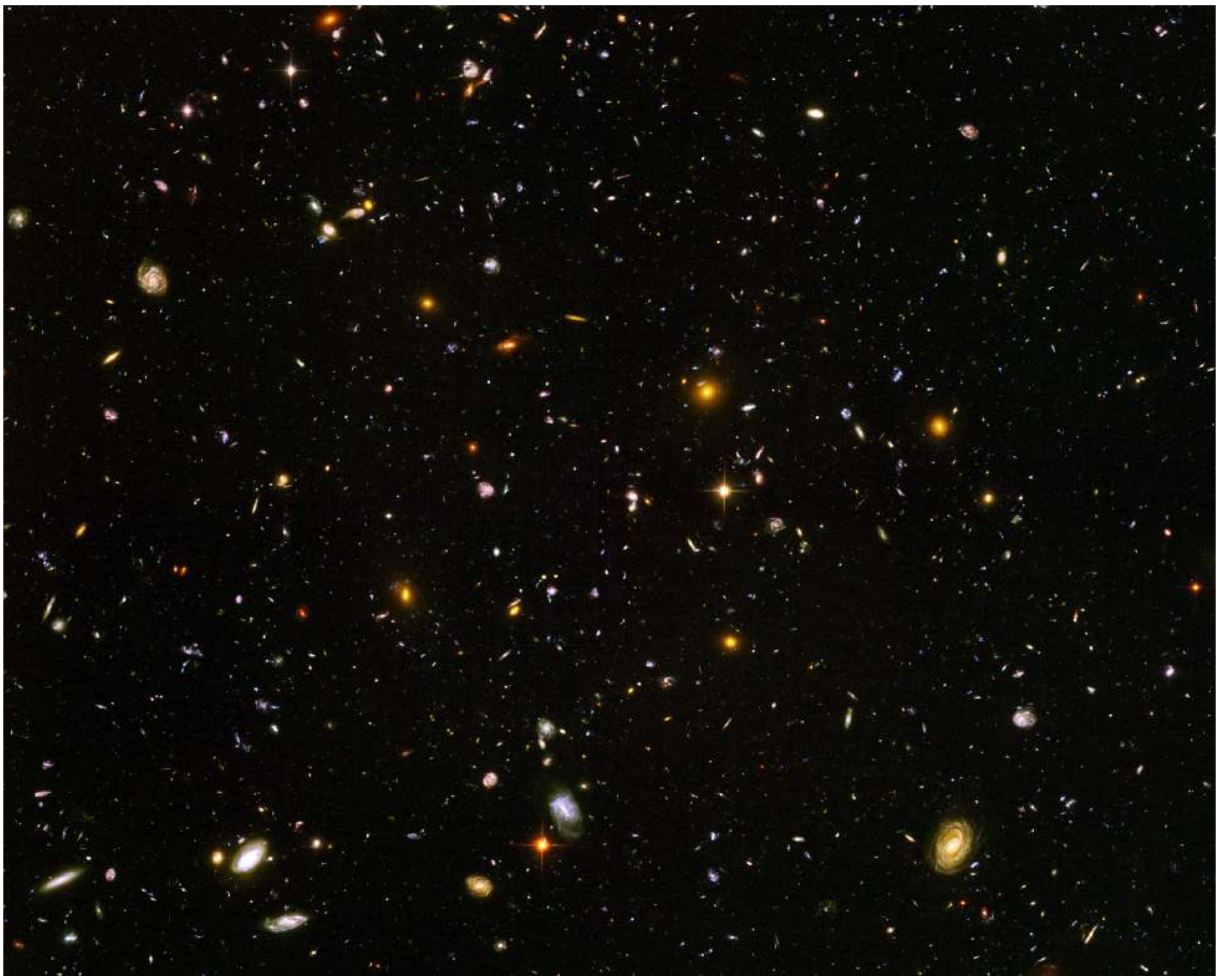

Figure 6.18: **The Hubble Ultra-Deep Field. This view of nearly 10,000 galaxies is the deepest light image of the cosmos,**

Figure 6.19: **The Sombrero Galaxy, Messier 104. The galaxy's hallmark is a brilliant white bulbous core, surrounded by dust lanes comprising the spiral structure of the galaxy.**

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Chapter 7

RADIO ASTRONOMY

7.1 Early history of radio astronomy

The electromagnetic equations of James Clerk Maxwell made it clear that radiation of all frequencies and wavelengths could reach the earth from distant sources in space. In the 19th century, several attempts to detect radio-frequency radiation from the sun were made, but these were unsuccessful because of lack of sensitivity of the instruments.

The first successful detection of radio-frequency radiation from the cosmos was made by Karl Jansky at Bell Labrotories in 1932. Jansky built an antenna designed to detect radiation at the frequensky of 20.5 MHz, corresponding to a wavelength of 14.6 meters. The antenna was mounted on a turntable which allowed it to be turned to explore all parts of the sky, and it had an aperture of approximately 100 feet. Colleagues christened it “Jansky’s Merry-Go-Round”.

Besides the radiation from nearby and distant thunderstorms, Jansky noticed faint signals which he at first thought were coming from the sun. However, on closer examination, he found that the periodicity of these signals was 23 hours and 56 minutes, rather than 24 hours. Jansky discussed this puzzling observation with a friend, the astrophysicist Albert Skellett, who pointed out to him that 23 hours and 56 minutes is the exact period of the rotation of the stars relative to the earth. Therefore the signals were not coming from the sun, but from outer space.

Jansky wanted to continue these investigations, but received no support from Bell Labrotories since the project was not related to communications. Nor did he receive support from the community of astrophysicists, for whom the idea of radio astronomy was too new to be appreciated.

Since his death from a heart condition in 1950, Jansky has been honored in many ways. The unit of energy flux from cosmic radio sources is named after him, as is a crater on the moon, as well as the National Radio Astronomy Observatory (NRAO) postdoctoral fellowship programme. Every year the NRAO awards their Jansky Prize. In 2012, a radio telescope in New Mexico was renamed the Karl G. Jansky Very Large Array. The asteroid 1932 Jansky is also named after him.

Figure 7.1: **Karl Jansky (1905-1950). Today he is recognized as the main founder of radio astronomy.**

Figure 7.2: **Full-size replica of Jansky's radio telescope, now at the Green Bank Observatory.**

7.2 Sir Martin Ryle and Anthony Hewish

Martin Ryle was born in Brighton, England, in 1918. He was the son of John Alfred Ryle, who later was appointed Professor of Social Medicine at Oxford University, and the nephew of Oxford's Professor of Philosophy, Gilbert Ryle.

After studying physics at Oxford, Martin Ryle served during World War II by helping to develop the use of radar to detect German air attacks. His work on radar is considered to have made a very significant contribution to England's victory in the "Battle of Britain".

After the war, Ryle received a fellowship to work at the Cavendish Laboratory of Cambridge University. Here, his work focused initially on radio emissions from the sun, but he soon became interested in radio sources outside our own galaxy. Here is an excerpt from his 1974 Nobel Lecture:

I think that the event which, more than anything else, led me to the search for ways of making more powerful radio telescopes, was the recognition, in 1952, that the intense source in the constellation of Cygnus was a distant galaxy - 1000 million light years away. This discovery showed that some galaxies were capable of producing radio emission about a million times more intense than that from our own Galaxy or the Andromeda nebula, and the mechanisms responsible were quite unknown. It seemed quite likely that some of the weaker sources already detected with the small radio telescopes then available might be similar in character; if so they would be at distances comparable with the limits of observation of the largest optical telescopes. It was therefore possible that more powerful radio telescopes might eventually provide the best way of distinguishing between different cosmological models. It was not until 1958 that it could be shown with some certainty that most of the sources were indeed powerful extragalactic objects, but the possibilities were so exciting even in 1952 that my colleagues and I set about the task of designing instruments capable of extending the observations to weaker and weaker sources, and of exploring their internal structure.

The problem of making radio telescopes with an effective aperture large enough to pinpoint very distant sources led Martin Ryle to develop the method of aperture synthesis, in which inputs from distant antennae are combined with corrected phases in such a way that their combined effect is equivalent to a radio telescope with an extremely large aperture. For this work, Martin Ryle received many honors, including the following:

- Elected a Fellow of the Royal Society (FRS) in 1952
- Hughes Medal (1954)
- Gold Medal of the Royal Astronomical Society (1964)
- Henry Draper Medal of the National Academy of Sciences (1965)
- Knight Bachelor (1966)
- Albert A. Michelson Medal of the Franklin Institute (1971)

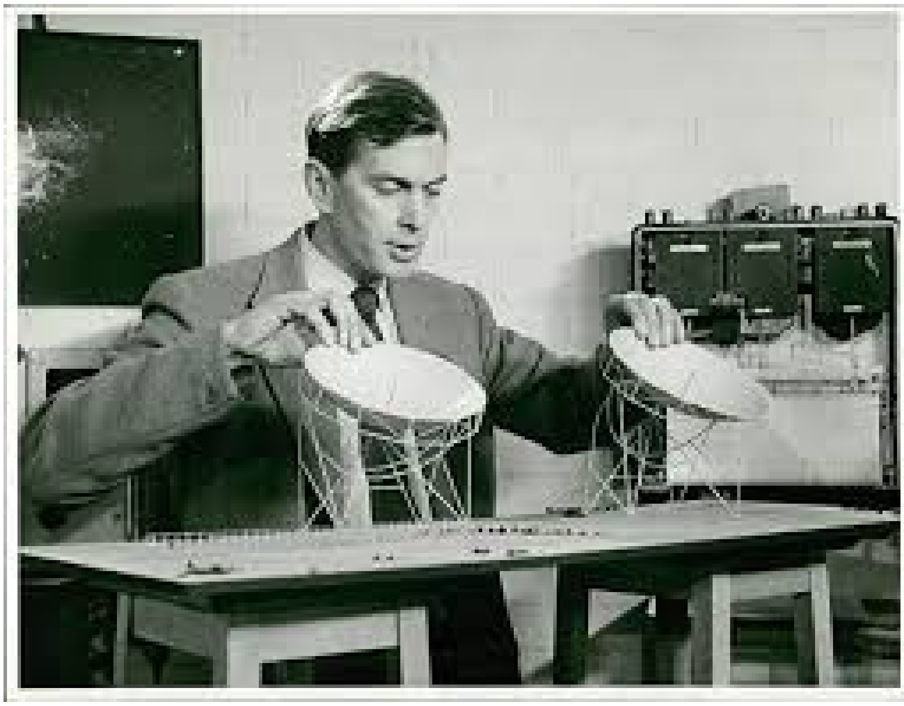

Figure 7.3: **Sir Martin Ryle (1918-1984).**

- Royal Medal (1973)
- Bruce Medal (1974)
- Nobel Prize in Physics (1974)
- Ryle Telescope at Mullard Radio Astronomy Observatory
- In 1965 Ryle co-delivered the Royal Institution Christmas Lecture on Exploration of the Universe.

From the mid 1970's onward, Sir Martin Ryle turned the main part of his attention towards social issues, which he considered to be more important. These included the following:

- Warning the world of the horrific dangers of nuclear armaments, notably in his pamphlet *Towards the Nuclear Holocaust.*
- Criticism of nuclear power, as in *Is there a case for nuclear power?*
- Research and promotion of alternative energy and energy efficiency, as in *Short-term Storage and Wind Power Availability.*
- Calling for the responsible use of science and technology. "...we should strive to see how the vast resources now diverted towards the destruction of life are turned instead to the solution of the problems which both rich - but especially the poor - countries of the world now face."

Figure 7.4: **Radio telescopes with aperture synthesis.**

Figure 7.5: **Anthony Hewish (born in 1924).**

7.3 Jocelyn Bell Burnell

Here is an excerpt form a September 5, 2018, article article by Laurel Wamsley entitled *In 1974, They Gave The Nobel To Her Supervisor. Now She's Won A $3 Million Prize* [1]

In 1967, Jocelyn Bell Burnell was a graduate student at Cambridge, working on a dissertation about strange objects in distant galaxies known as quasars.

She and her supervisor, Antony Hewish, had built a radio telescope to observe them. Data from the telescope scrolled out from a machine - a line in red ink, scrawling across 96 feet of chart paper each day.

As she pored over the data, she noticed something strange: "an unclassifiable squiggle," she recalls. It indicated mysterious radio waves, pulsing repeatedly.

She says she noticed the unusual signal only because she suffered from impostor syndrome: the idea that you're not good enough and at any moment, you may be discovered as a fraud. For Bell Burnell, it manifested as a fear she would be tossed out of Cambridge, she told The Guardian.

So she took more data from the telescope and kept scouring - but the blip vanished. A month later, the signal returned.

Bell Burnell brought the results to Hewish.

"He said, 'That settles it, it's manmade, it's artificial radio interference,'" she recounted to the newspaper. But she knew it couldn't be interference: The radio waves were coming from something moving at the same speed as the stars - meaning the source of the pulses had to be in space.

The dense objects responsible for the squiggles are now known as pulsars - rapidly spinning neutron stars that emit radiation. Their observation is considered one of the one of the greatest astronomical discoveries of the 20th century.

"The excitement was because this was a totally unexpected, totally new kind of object, behaving in a way that astronomers had never expected, never dreamt of," she said in a 2010 BBC documentary.

The discovery of pulsars was so important that it won a 1974 Nobel Prize - for Hewish.

Bell Burnell has said it doesn't bother her much that she wasn't included. "In those days students weren't recognized by the committee," she said in 2009.

Fifty years after Bell Burnell noticed that blip in the red ink, her observation has earned her a very big award: a Special Breakthrough Prize in Fundamental Physics, which comes with a check for $3 million.

[1] https://www.wuwm.com/post/1974-they-gave-nobel-her-supervisor-now-shes-won-3-million-prize

Figure 7.6: **Jocelyn Bell Burnell in 1968 at the Mullard Radio Astronomy Observatory at Cambridge University. She missed inclusion in the 1974 Nobel Prize in Physics, but later won a 3 million dollar award. She gave away the money to support scholarships.**

7.4 Quasars, pulsars, and neutron stars

Quasars

Here is a quotation from the Wikipedia article on quasars:

A quasar (also known as a quasi-stellar object abbreviated QSO) is an extremely luminous active galactic nucleus (AGN), in which a supermassive black hole with mass ranging from millions to billions of times the mass of the Sun is surrounded by a gaseous accretion disk. As gas in the disk falls towards the black hole, energy is released in the form of electromagnetic radiation, which can be observed across the electromagnetic spectrum. The power radiated by quasars is enormous: the most powerful quasars have luminosities thousands of times greater than a galaxy such as the Milky Way.

The term quasar originated as a contraction of quasi-stellar [star-like] radio source, because quasars were first identified during the 1950s as sources of radio-wave emission of unknown physical origin, and when identified in photographic images at visible wavelengths they resembled faint star-like points of light. High-resolution images of quasars, particularly from the Hubble Space Telescope, have demonstrated that quasars occur in the centers of galaxies, and that some host-galaxies are strongly interacting or merging galaxies. As with other categories of AGN, the observed properties of a quasar depend on many factors including the mass of the black hole, the rate of gas accretion, the orientation of the accretion disk relative to the observer, the presence or absence of a jet, and the degree of obscuration by gas and dust within the host galaxy.

Quasars are found over a very broad range of distances, and quasar discovery surveys have demonstrated that quasar activity was more common in the distant past. The peak epoch of quasar activity was approximately 10 billion years ago. As of 2017, the most distant known quasar is ULAS J1342+0928 at redshift z = 7.54; light observed from this quasar was emitted when the universe was only 690 million years old. The supermassive black hole in this quasar, estimated at 800 million solar masses, is the most distant black hole identified to date.

Pulsars

According to the Wikipedia article on pulsars,

A pulsar (from pulse and -ar as in quasar) is a highly magnetized rotating neutron star that emits beams of electromagnetic radiation out of its magnetic poles. This radiation can be observed only when a beam of emission is pointing toward Earth (much like the way a lighthouse can be seen only when the light is pointed in the direction of an observer), and is responsible for the pulsed appearance of emission. Neutron stars are very dense, and have short,

regular rotational periods. This produces a very precise interval between pulses that ranges from milliseconds to seconds for an individual pulsar. Pulsars are one of the candidates for the source of ultra-high-energy cosmic rays (see also centrifugal mechanism of acceleration).

The periods of pulsars make them very useful tools for astronomers. Observations of a pulsar in a binary neutron star system were used to indirectly confirm the existence of gravitational radiation. The first extrasolar planets were discovered around a pulsar, PSR B1257+12. Certain types of pulsars rival atomic clocks in their accuracy in keeping time.

Neutron stars

Here is a quotation from the Wikipedia article on neutron stars:

A neutron star is the collapsed core of a giant star which before collapse had a total mass of between 10 and 29 solar masses. Neutron stars are the smallest and densest stars, excluding black holes, hypothetical white holes, quark stars and strange stars. Neutron stars have a radius on the order of 10 kilometers (6.2 mi) and a mass of about 1.4 solar masses. They result from the supernova explosion of a massive star, combined with gravitational collapse, that compresses the core past white dwarf star density to that of atomic nuclei.

Once formed, they no longer actively generate heat, and cool over time; however, they may still evolve further through collision or accretion. Most of the basic models for these objects imply that neutron stars are composed almost entirely of neutrons (subatomic particles with no net electrical charge and with slightly larger mass than protons); the electrons and protons present in normal matter combine to produce neutrons at the conditions in a neutron star. Neutron stars are partially supported against further collapse by neutron degeneracy pressure, a phenomenon described by the Pauli exclusion principle, just as white dwarfs are supported against collapse by electron degeneracy pressure. However neutron degeneracy pressure is not by itself sufficient to hold up an object beyond 0.7M[solar] and repulsive nuclear forces play a larger role in supporting more massive neutron stars. If the remnant star has a mass exceeding the Tolman-Oppenheimer-Volkoff limit of around 2 solar masses, the combination of degeneracy pressure and nuclear forces is insufficient to support the neutron star and it continues collapsing to form a black hole.

Neutron stars that can be observed are very hot and typically have a surface temperature of around 600000 K. They are so dense that a normal-sized matchbox containing neutron-star material would have a weight of approximately 3 billion tonnes, the same weight as a 0.5 cubic kilometer chunk of the Earth (a cube with edges of about 800 meters) from Earth's surface. Their magnetic fields are between 108 and 1015 (100 million to 1 quadrillion) times stronger than Earth's magnetic field. The gravitational field at the neutron star's surface is about 2×10^{11} (200 billion) times that of Earth's gravitational

field.

As the star's core collapses, its rotation rate increases as a result of conservation of angular momentum, hence newly formed neutron stars rotate at up to several hundred times per second. Some neutron stars emit beams of electromagnetic radiation that make them detectable as pulsars. Indeed, the discovery of pulsars by Jocelyn Bell Burnell and Antony Hewish in 1967 was the first observational suggestion that neutron stars exist. The radiation from pulsars is thought to be primarily emitted from regions near their magnetic poles. If the magnetic poles do not coincide with the rotational axis of the neutron star, the emission beam will sweep the sky, and when seen from a distance, if the observer is somewhere in the path of the beam, it will appear as pulses of radiation coming from a fixed point in space (the so-called "lighthouse effect"). The fastest-spinning neutron star known is PSR J1748-2446ad, rotating at a rate of 716 times a second or 43,000 revolutions per minute, giving a linear speed at the surface on the order of 0.24 c (i.e. nearly a quarter the speed of light).

There are thought to be around 100 million neutron stars in the Milky Way, a figure obtained by estimating the number of stars that have undergone supernova explosions. However, most are old and cold, and neutron stars can only be easily detected in certain instances, such as if they are a pulsar or part of a binary system[why?]. Slow-rotating and non-accreting neutron stars are almost undetectable; however, since the Hubble Space Telescope detection of RX J185635-3754, a few nearby neutron stars that appear to emit only thermal radiation have been detected. Soft gamma repeaters are conjectured to be a type of neutron star with very strong magnetic fields, known as magnetars, or alternatively, neutron stars with fossil disks around them.

Neutron stars in binary systems can undergo accretion which typically makes the system bright in X-rays while the material falling onto the neutron star can form hotspots that rotate in and out of view in identified X-ray pulsar systems. Additionally, such accretion can "recycle" old pulsars and potentially cause them to gain mass and spin-up to very fast rotation rates, forming the so-called millisecond pulsars. These binary systems will continue to evolve, and eventually the companions can become compact objects such as white dwarfs or neutron stars themselves, though other possibilities include a complete destruction of the companion through ablation or merger. The merger of binary neutron stars may be the source of short-duration gamma-ray bursts and are likely strong sources of gravitational waves. In 2017, a direct detection (GW170817) of the gravitational waves from such an event was made, and gravitational waves have also been indirectly detected in a system where two neutron stars orbit each other.

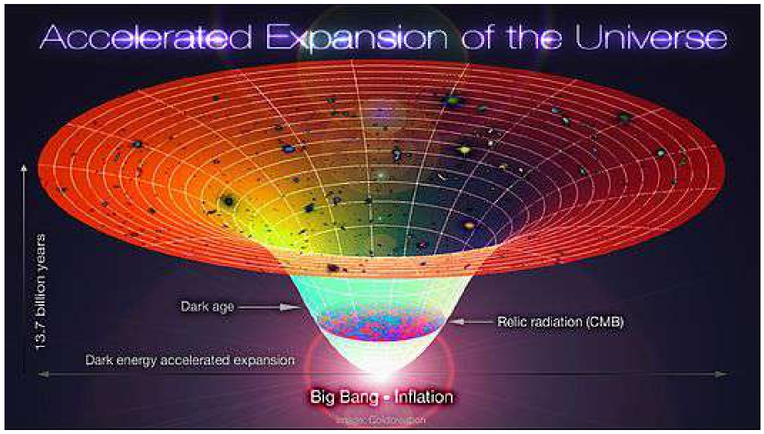

Figure 7.7: **The standard model of our universe.**

7.5 Penzias and Wilson

If the Universe is expanding, as Hubble's Law suggests, then it is logical to extrapolate backward in time, and to suppose that the Universe expanded outward from one place. According to this model this model, which is called the *Standard Model* of cosmology, or *Big Bang Theory*, the Universe exploded outward from an extremely hot and dense initial state, gradually cooling as it expanded.[2]

The Standard Model was first proposed 1927 by Georges Lemaitre and Alexander Friedmann on the basis of their solutions to Einstein's general relativistic equations. In 1929 the model was supported by Hubble's discoveries. Until the late 1950's, there were competing models, such as the Steady State Cosmology proposed by Fred Hoyle. However in more recent times, very strong evidence has accumulated to support the Standard Model. This evidence includes the large-scale structure of the Universe, the abundances of elements.

Crucial evidence supporting the Standard Model was discovered by accident in 1964. Working at the Bell Laboratories in New Jersey, Arno Penzias and Robert Woodrow Wilson were experimenting with a super-sensitive 6 meter microwave horn antenna designed to pick up the signals from radio waves bounced off Echo balloon satellites. They tried to remove all the interfering signals from radar and radio broadcasts by cooling their receiver with liquid helium. However, despite their efforts, they could not get rid of a mysterious microwave background radiation that seemed to be coming equally from all directions, both day and night. They had no idea of what was causing this mysterious background.

Meanwhile, at Princeton University, only sixty miles away, astrophysicists Robert H. Dicke, Jim Peebls and David Wilkinson, building on the earlier work of George Gamow, had written a paper on the cosmic background radiation that they thought should be present on theoretical grounds. During the expansion and cooling of the Universe, a moment occurred when atoms formed, and the radiation characteristic of the temperature at that

[2]Today this initial state is believed to have been infinitely hot and infinitely dense, i.e. a *singularity*.

Figure 7.8: **Arno Penzias and Robert Woodrow Wilson, discoverers of the echo of the Big Bang.**

time was suddenly free to propagate outward. By now, the Princeton group calculated, this radiation should be red shifted so far that it would now lie in the microwave region.

As it happened, Bernard F. Burke of MIT knew of both the Bell Labs experiments and the Princeton group's theoretical work. He brought them all together, and a joint publication was arranged. In 1978, Penzias and Wilson were awarded a Nobel Prize in Physics for their experimental discovery of what might be called "the echo of the Big Bang". This was the crucial piece of evidence supporting the Standard Model.

Today, our Universe is believed to be 13.72 billion years old. When it cooled enough for atoms to form, only hydrogen extremely small amounts of helium were present. The heavier elements are thought to have been synthesized through nuclear reactions in the interior of stars.

The Wikipedia article on stellar evolution states that:

All stars are born from collapsing clouds of gas and dust... Over the course of millions of years, these protostars settle down into a state of equilibrium, becoming what is known as a main-sequence star.

Nuclear fusion powers a star for most of its life. Initially the energy is generated by the fusion of hydrogen atoms at the core of the main-sequence star. Later, as the preponderance of atoms at the core becomes helium, stars like the Sun begin to fuse hydrogen along a spherical shell surrounding the core. This process causes the star to gradually grow in size, passing through the subgiant stage until it reaches the red giant phase. Stars with at least half the mass of the Sun can also begin to generate energy through the fusion of helium at their core, whereas more-massive stars can fuse heavier elements along a series of concentric shells. Once a star like the Sun has exhausted its

nuclear fuel, its core collapses into a dense white dwarf and the outer layers are expelled as a planetary nebula. Stars with around ten or more times the mass of the Sun can explode in a supernova as their inert iron cores collapse into an extremely dense neutron star or black hole. Although the universe is not old enough for any of the smallest red dwarfs to have reached the end of their lives, stellar models suggest they will slowly become brighter and hotter before running out of hydrogen fuel and becoming low-mass white dwarfs.

Our local star, the sun, is middle-sized and middle-aged. It was formed an estimated 4.6 billion years ago, and will last another 5 billion years or so before expanding into a red giant. At the moment it lies of the main sequence in the temperature-luminosity diagram. Evidence from abundances of radioactive elements and their decay products indicates that our earth was formed soon after the sun, roughly 4.54 billion years ago.

Modern astronomy has shown the Universe to be almost unimaginably large. Wikipedia states that: "The size of the Universe is unknown; it may be infinite. The region visible from Earth (the observable universe) is a sphere with a radius of about 46 billion light years, based on where the expansion of space has taken the most distant objects observed. For comparison, the diameter of a typical galaxy is 30,000 light-years, and the typical distance between two neighboring galaxies is 3 million light-years. As an example, the Milky Way Galaxy is roughly 100,000 light years in diameter, and the nearest sister galaxy to the Milky Way, the Andromeda Galaxy, is located roughly 2.5 million light years away. There are probably more than 100 billion (10^{11}) galaxies in the observable Universe.Typical galaxies range from dwarfs with as few as ten million (10^7) stars up to giants with one trillion(10^{12}) stars, all orbiting the galaxy's center of mass. A 2010 study by astronomers estimated that the observable Universe contains 300 sextillion (3×10^{23}) stars."

Among this incredibly vast number of stars it is believed that there are innumerable stars that have planets similar to the Earth and hence able to support life. We also now know that given conditions that are favorable to life, it will almost certainly develop and evolve. The Earth seems to be only of extremely minor importance on the scale of the Universe. Given these facts, and given that the fundamental laws of nature are mathematical, it is difficult to maintain that the entire Universe and the laws that govern it were arranged for the benefit of humans, especially since humans have only existed for a brief instant on the time-scale of the Universe. If asked where the Universe came from and why, the scientist must answer with honesty, "I don't know".

Some excerpts from Arno Penzias' biographical Nobel Lecture

Arno Penzias was born in 1933 in Munich Germany to a Jewish family. The family narrowly escaped being sent to a Nazi concentration camp, and escaped from Germany, first to England and afterwards to America. Penzias became a radio astronomer, and went to Bell Laboratories with the aim of completing studies that he had begun while writing his Ph.D. thesis. There he and Robert Woodrow Wilson discovered the "echo of the Big Bang", a discovery for which they shared the 1978 Nobel Prize in Physics. Here are some excerpts from Penzias' Nobel Lecture:

...In 1961, with my PhD thesis complete, I went in search of a temporary job at Bell Laboratories, Holmdel, New Jersey. Their unique facilities made it an ideal place to finish the observations I had begun during my thesis work. "Why not take a permanent job? You can always quit," was the advice of Rudi Kompfner, then Director of the Radio Research Laboratory. I took his advice, and remained a Bell Labs employee for the next thirty seven years.

Since the large horn antenna I had planned to use for radio-astronomy was still engaged in the ECHO satellite project for which it was originally constructed, I looked for something interesting to do with a smaller fixed antenna. The project I hit upon was a search for line emission from the then still undetected interstellar OH molecule. While the first detection of this molecule was made by another group, I learned quite a bit from the experience.

In order to make some reasonable estimate of the excitation of the molecule, I adopted the formalism outlined by George Field in his study of atomic hydrogen. To make sure that I had it right, I took my calculation to him for checking. One of the factors in that calculation was the radiation temperature of space at the line wavelength, 18-cm. I used 2 K, a somewhat larger value than he had used earlier, because I knew that at least two measurements at Bell Laboratories had indications of a sky noise temperature in excess of this amount, and because I had noticed in Gerhard Hertzberg's "Spectra of Diatomic Molecules" that interstellar CN was known to be excited to this temperature. The results of this calculation were used and then forgotten. It was not until Dr. Field reminded me of them in December of 1966 that I had any recollection of my momentary involvement with what was later shown (by Field and others) to be observational astronomy's first encounter with the primordial radiation that permeates our Universe.

In the meantime, others at Bell Labs pressed the horn antenna into service for another satellite project. A new Bell System satellite, TELSTAR, was due to be launched in mid-1962. While the primary earth station at Andover, Maine, was more or less on schedule, it was feared that the European partners in the project would not be ready at launch time, leaving Andover with no one to talk to. As it turned out, fitting the Holmdel horn with a 7-cm receiver for TELSTAR proved unnecessary; the Europeans were ready at launch time. This left the Holmdel horn and its beautiful new ultra low-noise 7-cm traveling wave maser available to me for radio astronomy. This stroke of good fortune came at just the right moment. A second radio astronomer, Robert Wilson, came from Caltech on a job interview and was hired. After finishing separate projects, we set to work early in 1963.

In putting our radio astronomy receiving system together we were anxious to make sure that the quality of the components we added were worthy of the superb properties of the horn antenna and maser that we had been given. We

began a series of radio astronomical observations, ones that I had proposed so as to make the best use of the careful calibration and extreme sensitivity of our system. Of these projects, the most technically challenging was a measurement of the radiation intensity from our galaxy at high latitudes. This multi-year endeavor, which resulted in our discovery of the cosmic microwave background radiation, is described in Wilson's Nobel lecture...

Suggestions for further reading

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Chapter 8

CHANDRASEKHAR

8.1 Early life and career

Subrahmanyan Chandrasekhar was born in 1910 in Lahore, Punjab, British India. His paternal uncle was Sir Chandrashekhara Venkata Raman (1888-1970), who won the 1930 Nobel Prize in Physics for his studies of light scattering. His mother was highly intellectual too, and had, for example, translated Ibsen's *A Doll's House* into Tamil.

During his first 12 years, Chandrasekhar was tutored at home. He later studied at the Hindu Highschool and Presidency College, both in Madras. At he age of 19, while still a student, Chandrasekhar wrote his first paper, *Compton Scattering and the New Statistics.*

In 1930, Chandrasekhar won a Government of India Scholarship for study at the University of Cambridge, where his admission to Trinity College was arranged by Prof. R.A. Fowler. While at Cambridge, Chandrasekhar worked on the statistical mechanics of the degenerate electron gas of white dwarf stars. He provided relativistic corrections to Fowler's previous work in the field. On the advice of P.A.M. Dirac, Chandrasekhar spent a year at Niels Bohr's Institute for Theoretical Physics in Copenhagen.

In 1937, while on a visit to the United States, Chandrasekhar was invited to join the faculty of the University of Chicago. After some hesitation, he accepted the offer, and despite numerous offers from other universities, he remained at the University of Chicago until his death in 1995.

When I was a postgraduate student at the University of Chicago in 1955, I attended a course in Mathematical Methods taught by Chandrasekhar. While teaching the course, he drove down to Chicago once a week from Yerkes Observatory in Wisconsin, which was part of the university, and where he did much of his work. As a teacher. Chandrasekhar was inspiring, but severe. If there was any whispering at the back of the class, he clapped his hands sharply and brought us to attention. He loved Bessel functions, and transmitted this love to us. He spoke and dressed like a very distinguished English gentleman. He was a handsome man, with a slight streak of white in his hair, which added to his commanding presence.

Figure 8.1: **Subrahmanyan Chandrasekhar (1910-1995).**

At the dormitory group where I lived, there was a "physics table", where all of us who were studying physics could eat together. One day we invited Prof. Chandrasekhar to visit our table for dinner, and he accepted. During the dinner, he tried to persuade as many of us as possible to change our studies and to become astrophysicists. He had a good argument to persuade us. He said that astronomy offered the possibility of observing extreme conditions that could never be duplicated in a laboratory. for example, extremes of density, temperature, magnetic fields, or system size. Therefore, astrophysics offered the possibility of discovering physical phenomena that could not be discovered in any other way. Two of my friends, Donat Wentzel and Peter Vandervoort, were convinced by his argument, and they both had fine careers in astrophysics.

Below we look at some of the fields in which Chandrasekhar did pioneering work.

8.2 Magnetohydrodynamics

The Earth's magnetic field

Inside the Earth, the decay of radioactive elements is constantly producing heat. As this heat is transferred outward, convection currents are produced in the Earth's interior. Because the core is composed of molten iron, which is an electrical conductor, the currents produce a magnetic field. The flow is influenced both by the existing magnetic field, and by forces arising from the rotation of the Earth.

Chandrasekhar used his great power as a mathematician to solve the extremely complex magnetohydrodynamic equations describing this situation, and to find the conditions for stability. His results fit with what is known to have happened to the Earth's magnetic field from the dating of fields trapped in volcanic rocks. The magnetic north pole remains near to the geographical north for long periods of time, but gradually weakens in strength, and then suddenly reverses in direction, so that the magnetic north and south exchange their positions, but still stay close to the geographical north and south poles of the Earth. The magnetic fields gradually grow in strength, reach a maximum, weaken again, and then once again exchange polarity so that the magnetic north pole is once again located near to the geographical north. There have been 183 such reversals of polarity during the last 83 million years.

The solar magnetic activity cycle

Sunspots were observer by Galileo and by his contemporary Italian Jesuit astronomers, with whom Galileo had a conflict about the priority of the observation. Later, in 1775, the Danish astronomer Christian Horrebow wrote that "It appears that after the course of a certain number of years, the appearance of the Sun repeats itself with respect to the number and size of the spots". These and other observations on the sunspot cycle were collected and published by the Swiss astronomer Rudolf Wolf (1816-1893).

In 1908, George Ellory Hale in the United States showed that sunspots are strongly magnetic. This was the first observation of magnetic fields outside the Earth. Later research has given us the following picture of the sunspot cycle:

Great amounts of heat are generated by nuclear reactions in the interior of the Sun. Convection currents carrying this heat outward interact with the existing magnetic field because the atoms in the interior of the sun are ionized. The mixture of electrons and atomic nuclei is called a "plasma", and it is an electrical conductor. The problem of analyzing such a magnetohydrodynamic system is a very complex one, but Chandrasekhar's powerful mathematical methods produced solutions which agree with the observed facts.

The spots which we observe on the sun are in fact places where strong magnetic lines of force loop outward into space in the Sun's northern hemisphere. After looping outward, these lines of force return to the Sun's interior in the southern hemisphere. Thus the magnetic lines of force surrounding the Sun resemble those surrounding a bar magnet, looping outward at the north pole and inward at the south pole, just as is the case for the Earth. Just as is the case for the Earth, the Sun's magnetic activity goes through a cycle, becoming stronger, reaching a maximum, then becoming weaker, and then reversing polarity. However the Sun's magnetic field is much stronger than that of the Earth because the amounts of energy generated in its interior are much greater. Correspondingly, the cycle is both shorter and more regular. A single reversal takes 11 years, and the complete cycle, with two reversals, bring us back to the original polarity, takes 22 years.

Highly magnetic stars

Here is an excerpt from an October 11, 2019, article by Jake Parks, published in Astronomy[1]:

[1] http://www.astronomy.com/news/2019/10/merging-stars-may-create-the-universes-most-powerful-magnets

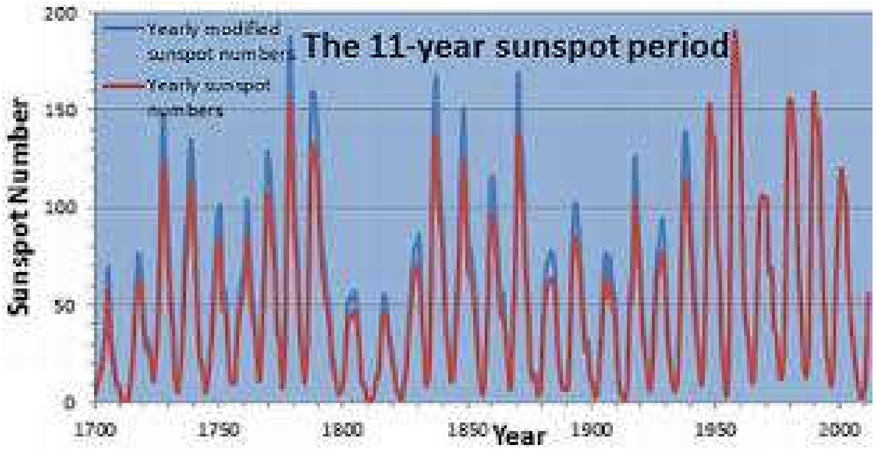

Figure 8.2: **Cycles of sunspot activity.**

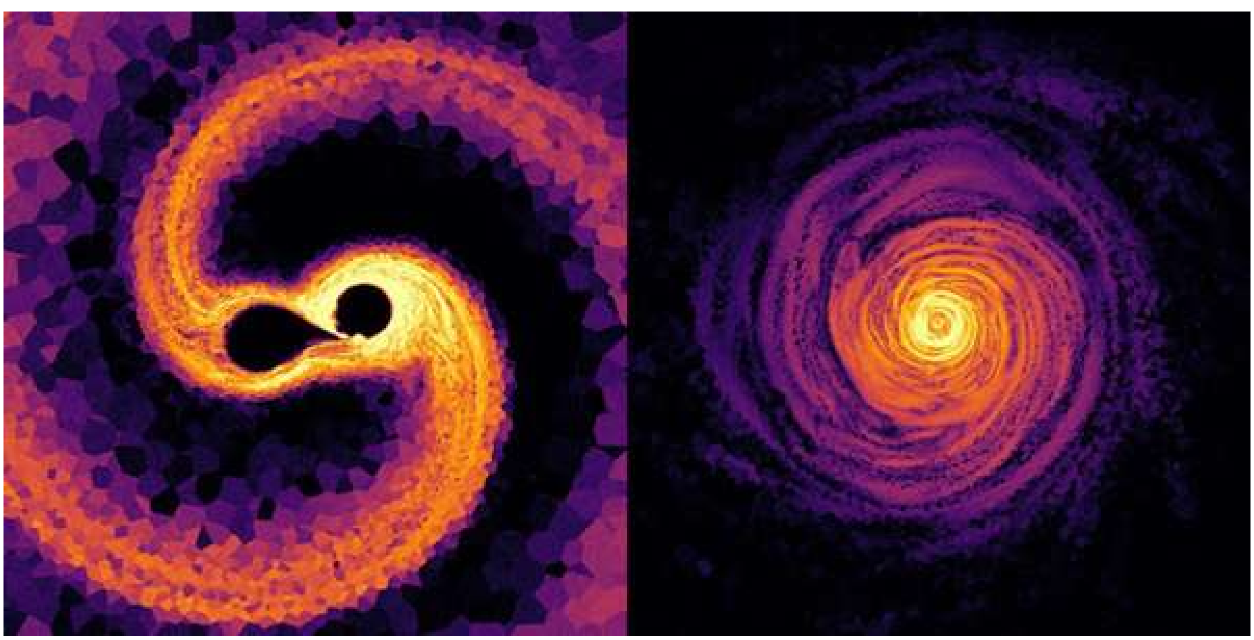

Figure 8.3: **The merging of two stars to form a highly magnetic star.**

More than 60 years ago, astronomers realized about 10 percent of massive stars have powerful magnetic fields bursting from their surfaces. But the exact origins of these magnetic fields - which can reach hundreds to thousands of times the strength of the Sun's - has so far remained a mystery.

The answer, it turns out, may be due to a collision between two normal stars.

A team of scientists recently used cutting-edge simulations to uncover an evolutionary path they think explains the formation of extremely magnetic stars. And as a cherry on top, their findings may also shed light on the origins of a slew of other astronomical oddities. These mysteries include magnetars (a rare type of hyper-magnetic neutron star), blue stragglers (massive stars that appear too young for their age), and maybe even enigmatic cosmic events like fast radio bursts and super-luminous supernovae.

8.3 The formation and evolution of stars

Protostars form from clouds of interstellar gas. The gas is not entirely uniform and gravitation makes regions of high density become even more dense. As more and more matter falls into such a region, potential energy is converted into heat. Finally the dense region becomes a protostar, hot enough so that nuclear fusion reactions can take place. The primary reaction is the fusion of hydrogen nuclei to form helium.

The evolution and ultimate fate of a protostar depend on its mass. Our own Sun is a star of medium mass, and it is predicted that in approximately 5 billion years, the Sun will expand and become a red giant. Stars less massive than the Sun have lemger lifetimes, while in stars whose mass is greater than the solar mass, the lifetime can be much shorter.

The Hertzsprung-Russell diagram is a plot of temperature versus luminosity, as is illustrated in Figures 8.5 and 8.6. It was developed by the Danish astronomer Ejnar Hertzsprung (1873-1967) and by Henry Norris Russell (1877-1957) from the United States. The *main sequence* is the well-populated diagonal line running from the lower right of the Hertzsprung-Russell diagram to the upper left. During their evolution, most stars start by drifting over to the the main sequence. They remain there for most of their lives. What happens next depends on the star's mass. As is shown in Figure 8.4, after spending time on the main sequence of the Hertzsprung-Russell diagram, high-mass stars can become supernovae, and neutron stars, or even black holes. On the other hand, stars of lower mass, after spending a very long time on the main sequence, can become red giants. Whether or not they end as white dwarfs depends on their exact mass, as we shall see below.

In their life cycles, high-mass stars can go through stages in which heavy elements are built up in the nuclear reactions that take place in their interiors. If they later explode as supernovae, these heavy elements are scattered widely in interstellar space. Our own solar system benefited from the dust of the past explosion of a supernova, and that is why the Earth contains the heavy elements on which the phenomenon of life depends.

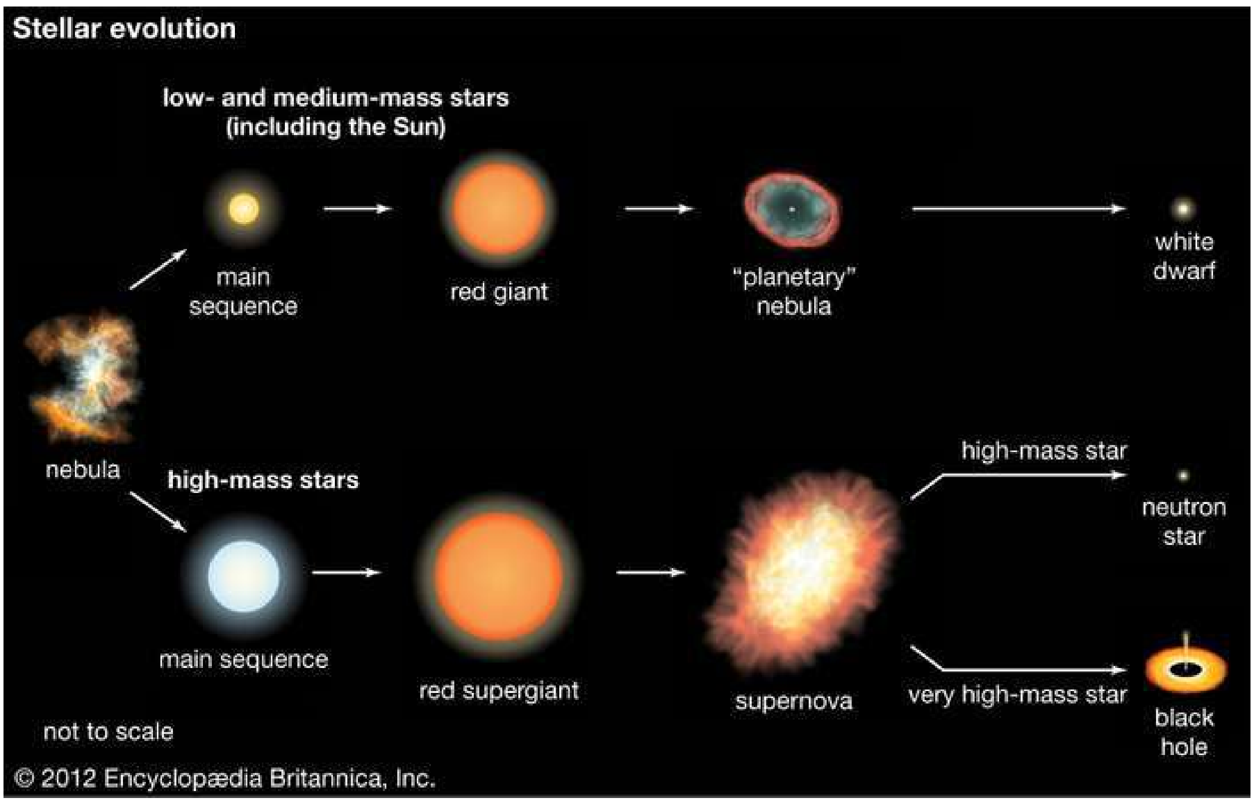

Figure 8.4: **The evolution and ultimate fate of a star depend on its mass.**

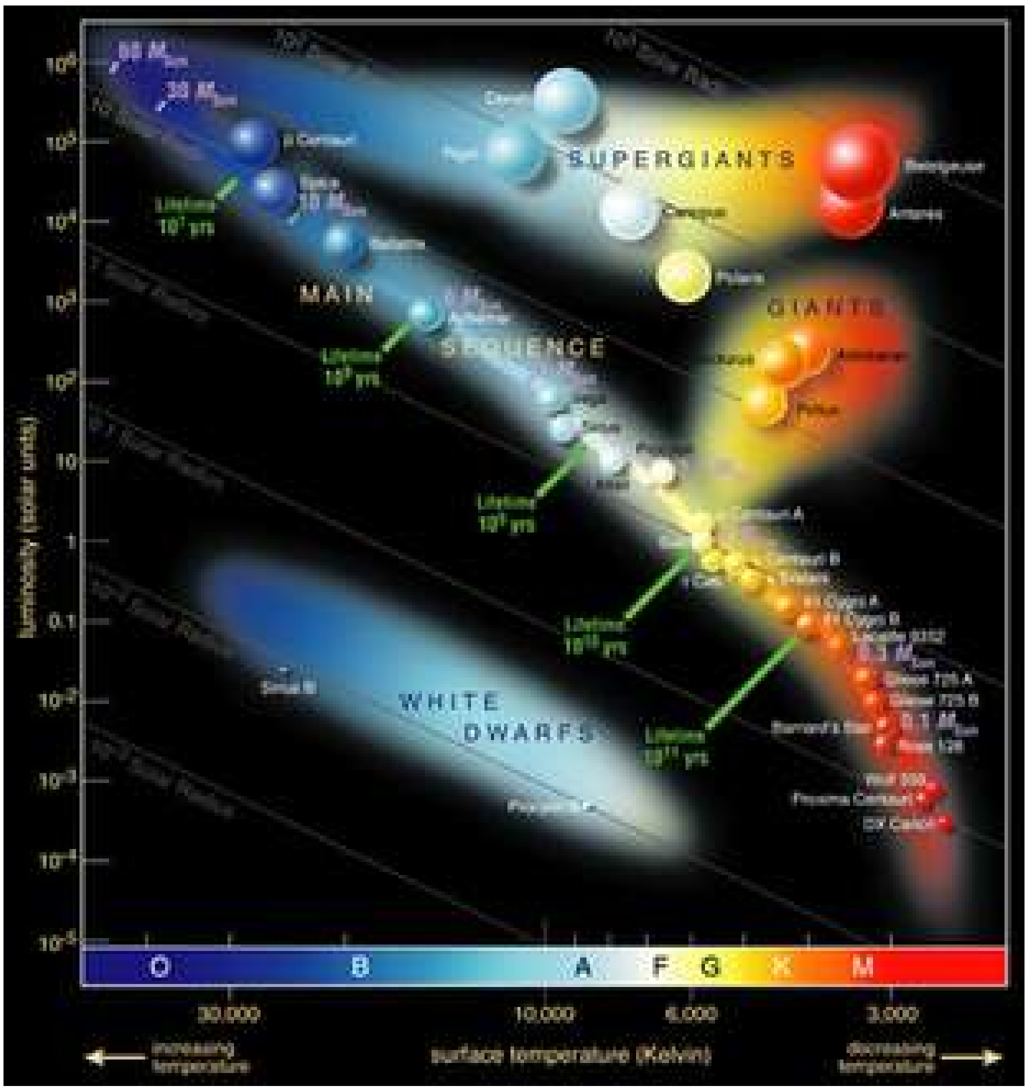

Figure 8.5: **A Hertzsprung-Russell diagram showing many well-known stars in the Milky Way.**

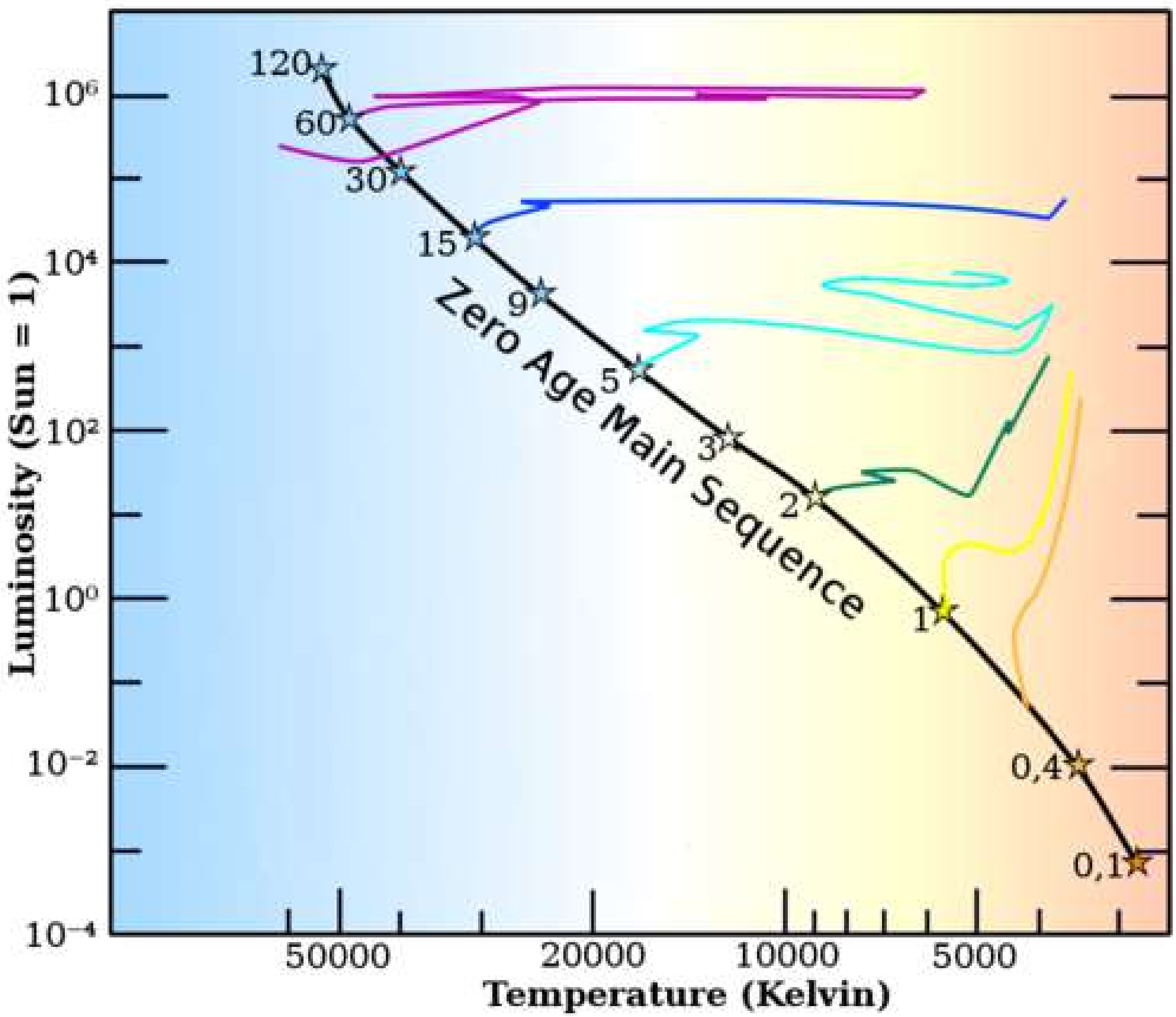

Figure 8.6: **The evolutionary tracks of stars with different initial masses on the Hertzsprung-Russell diagram. The tracks start once the star has evolved to the main sequence and stop when fusion stops (for massive stars) and at the end of the red giant branch (for stars 1 solar mass and less).**

8.4 Black holes: The Chandrasekhar limit

The *Chandrasekhar limit* is an upper limit to the mass of a white dwarf star, above which it must collapse into a neutron star or a black hole. Previous estimates of this limits were improved by the 20-year-old Subramyan Chandrasekhar, who added relativistic corrections to the model of the electrons in white dwarf stars as a Fermi gas, whose equilibrium was supported by the Pauli exclusion principle. The value which he found, 2.765×10^{30} kg. or roughly 1.4 times the solar mass, is today considered to be entirely correct. However, Chandrasekhar's pioneering work was ignored by the astronomical community of the time because condescending remarks of Sir Arthur Eddington, who said. "The star has to go on radiating and radiating and contracting and contracting until, I suppose, it gets down to a few km radius, when gravity becomes strong enough to hold in the radiation, and the star can at last find peace. I think there should be a law of Nature to prevent a star from behaving in this absurd way!". Eddington refused to believe that black holes could exist, and continued in this belief until the end of his career.

In his biography of Chandrasekhar, Arthur I Miller wrote: "Chandra's discovery might well have transformed and accelerated developments in both physics and astrophysics in the 1930s. Instead, Eddington's heavy-handed intervention lent weighty support to the conservative community astrophysicists, who steadfastly refused even to consider the idea that stars might collapse to nothing. As a result, Chandra's work was almost forgotten."

Chandrasekhar's work in this field was finally given the recognition that it deserved, and it is especially mentioned in his 1983 Nobel Prize in Physics citation.

8.5 Chandrasekhar's Nobel Prize in Physics

Some excerpts from Chandrasekhar's biographical Nobel Lecture

...After the early preparatory years, my scientific work has followed a certain pattern motivated, principally, by a quest after perspectives. In practise, this quest has consisted in my choosing (after some trials and tribulations) a certain area which appears amenable to cultivation and compatible with my taste, abilities, and temperament. And when after some years of study, I feel that I have accumulated a sufficient body of knowledge and achieved a view of my own, I have the urge to present my point of view, ab initio, in a coherent account with order, form, and structure.

There have been seven such periods in my life: stellar structure, including the theory of white dwarfs (1929-1939); stellar dynamics, including the theory of Brownian motion (1938-1943); the theory of radiative transfer, including the theory of stellar atmospheres and the quantum theory of the negative ion of hydrogen and the theory of planetary atmospheres, including the theory of the illumination and the polarization of the sunlit sky (1943-1950); hydrodynamic and hydromagnetic stability, including the theory of the Rayleigh-Bénard con-

vection (1952-1961); the equilibrium and the stability of ellipsoidal figures of equilibrium, partly in collaboration with Norman R. Lebovitz (1961-1968); the general theory of relativity and relativistic astrophysics (1962-1971); and the mathematical theory of black holes (1974- 1983). The monographs which resulted from these several periods are:

1. An Introduction to the Study of Stellar Structure (1939, University of Chicago Press; reprinted by Dover Publications, Inc., 1967).
2. (a) Principles of Stellar Dynamics (1943, University of Chicago Press; reprinted by Dover Publications, Inc., 1960), and (b) *Stochastic Problems in Physics and Astronomy*, Reviews of Modern Physics, 15, 1 - 89 (1943); reprinted in Selected Papers on Noise and Stochastic Processes by Nelson Wax, Dover Publications, Inc., 1954.
3. Radiative Transfer (1950, Clarendon Press, Oxford; reprinted by Dover Publications, Inc., 1960).
4. Hydrodynamic and Hydromagnetic Stability (1961, Clarendon Press, Oxford; reprinted by Dover Publications, Inc., 1981).
5. Ellipsoidal Figures of Equilibrium (1968; Yale University Press).
6. The Mathematical Theory of Black Holes (1983, Clarendon Press, Oxford).

However, the work which appears to be singled out in the citation for the award of the Nobel Prize is included in the following papers:

- *The highly collapsed configurations of a stellar mass*, Mon. Not. Roy. Astron. Soc., 91, 456-66 (1931).
- *The maximum mass of ideal white dwarfs*, Astrophys. J., 74, 81 - 2 (1931).
- *The density of white dwarfstars*, Phil. Mag., 11, 592 - 96 (1931).
- *Some remarks on the state of matter in the interior of stars*, Z. f. Astrophysik, 5, 321-27 (1932).
- *The physical state of matter in the interior of stars*, Observatory, 57, 93 - 9 (1934)
- *Stellar configurations with degenerate cores*, Observatory, 57, 373 - 77 (1934).
- *The highly collapsed configurations of a stellar mass* (second paper), Mon. Not. Roy. Astron. Soc., 95, 207 - 25 (1935).
- *Stellar configurations with degenerate cores*, Mon. Not. Roy. Astron. Soc., 95, 226-60 (1935).
- *Stellar configurations with degenerate cores* (second paper), Mon. Not. Roy. Astron. Soc., 95, 676 - 93 (1935).
- *The pressure in the interior of a star*, Mon. Not. Roy. Astron. Soc., 96, 644 - 47 (1936).

- ***On the maximum possible central radiation pressure in a star of a given mass***, **Observatory, 59, 47 - 8 (1936).**
- ***Dynamical instability of gaseous masses approaching the Schwarzschild limit in general relativity***, **Phys. Rev. Lett., 12, 114 - 16 (1964); Erratum, Phys. Rev. Lett., 12, 437 - 38 (1964).**
- ***The dynamical instability of the white-dwarf configurations approaching the limiting mass*** **(with Robert F. Tooper), Astrophys. J., 139, 1396 - 98 (1964).**
- ***The dynamical instability of gaseous masses approaching the Schwarzschild limit in general relativity***, **Astrophys. J., 140, 417 - 33 (1964).**
- ***Solutions of two problems in the theory of gravitational radiation***, **Phys. Rev. Lett., 24, 611 - 15 (1970); Erratum, Phys. Rev. Lett., 24, 762 (1970).**
- ***The effect of graviational radiation on the secular stability of the Maclaurin spheroid***, **Astrophys. J., 161, 561 - 69**

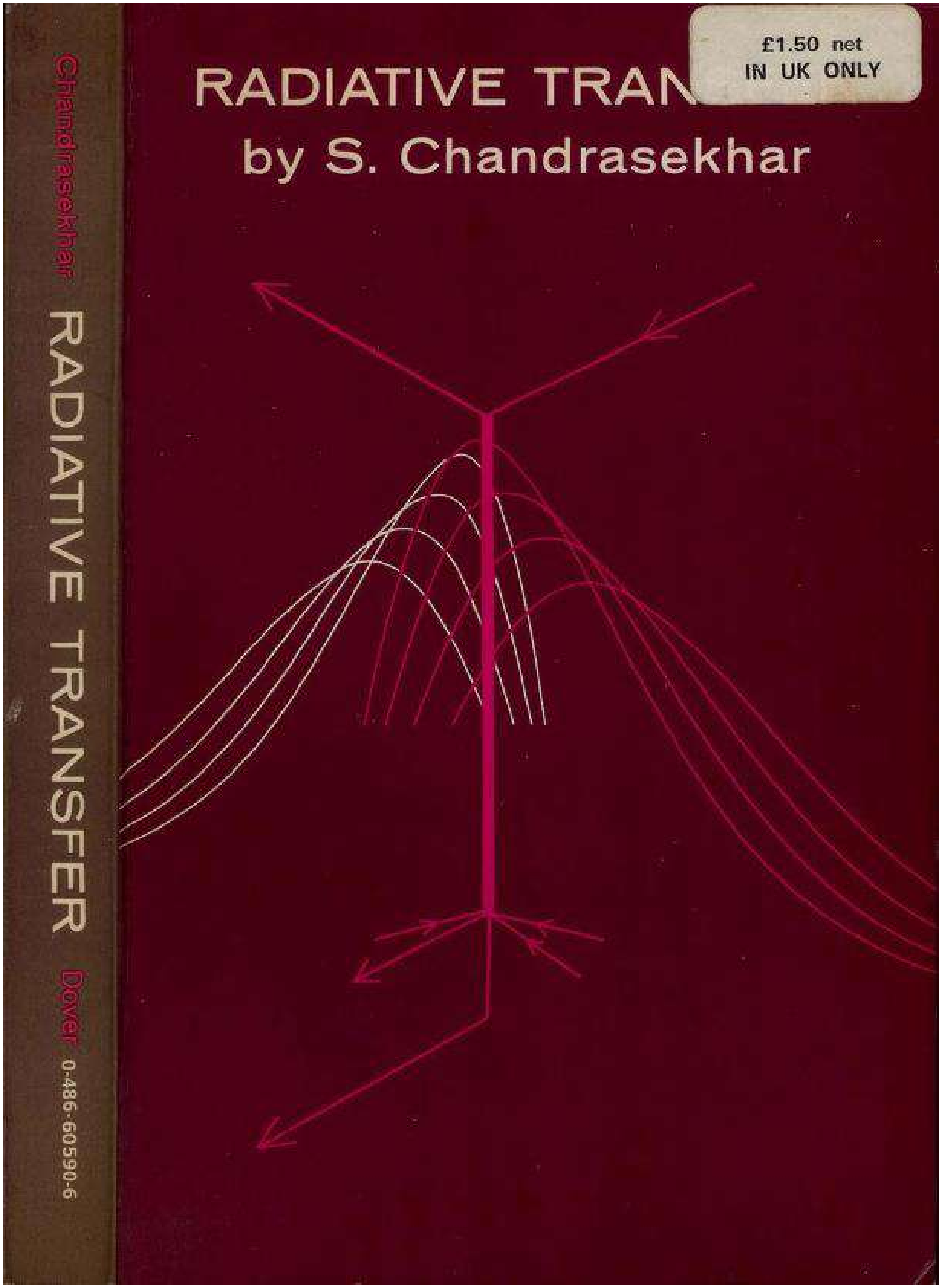

Figure 8.7: **Chandrasekhar's famous book on radiative transfer in stellar interiors.**

Suggestions for further reading

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2. Chandrasekhar, S. (2005) [1942]. Principles of Stellar Dynamics. New York: Dover.
3. Chandrasekhar, S. (1960) [1950]. *Radiative Transfer*. New York: Dover.
4. Chandrasekhar, S. (1975) [1960]. *Plasma Physics*. Chicago: The University of Chicago Press.
5. Chandrasekhar, S. (1981) [1961]. *Hydrodynamic and Hydromagnetic Stability*. New York: Dover.
6. Chandrasekhar, S. (1987) [1969]. *Ellipsoidal Figures of Equilibrium*. New York: Dover.
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Chapter 9

HAWKING, PENROSE AND HIGGS

9.1 Penrose-Hawking singularity theorems

Roger Penrose

Roger Penrose was born in Colchester, England in 1931. His father was the psychiatrist and geneticist Leonal Penrose, and his grandfather was the physiologist John Berisford Leathes. His brother Oliver Penrose is also a distinguishes physicist, and another brother, Johnathan Penrose, a chess Grandmaster.

While still a student at University College, London, Penrose proposed a new method for taking the inverse of matrices (the Moore-Penrose inverse). Penrose finished his Ph.D. at Cambridge University with a thesis entitled "Tensor methods in algebraic geometry". Later his attention was drawn from pure mathematics to astronomy by the Cambridge cosmologist Dennis Sciama.

In 1964, Penrose revolutionized the mathematical tools used to analyze the structure of the space-time continuum. Previously, in the general theory of relativity, solutions to Einstein's equations were confined to cases of high symmetry. For example, Schwartzchild's solutions were restricted to static systems with spherical symmetry. Also perturbation theory had been used by Wheeler to treat more general cases, but large deviations from symmetry were out of reach. Penrose liberated the subject by focusing, not on the details of the solutions to Einstein's equations, but on their topology. This revolutionary approach led him to the Penrose-Hawking singularity theorems, for which he and Hawking shared the prestigious Wolfson Foundation Prize in Physics in 1988. The citation was as follows:"for their brilliant development of the theory of general relativity, in which they have shown the necessity for cosmological singularities and have elucidated the physics of black holes. In this work they have greatly enlarged our understanding of the origin and possible fate of the Universe."

Roger Penrose has received numerous other honors and awards for his work in astrophysics. Among them are the following;

- In 1988 he shared the Wolfson Foundation Prize for Physics..
- In 1989 he was awarded the Dirac Medal and Prize of the British Institute of Physics.
- In 1990 Penrose was awarded the Albert Einstein Medal for outstanding work related to the work of Albert Einstein by the Albert Einstein Society.
- In 1991, he was awarded the Naylor Prize of the London Mathematical Society.
- From 1992 to 1995 he served as President of the International Society on General Relativity and Gravitation.
- In 1994, Penrose was knighted for services to science.
- In 1994 he was also awarded an Honorary Degree (Doctor of Science) by the University of Bath.
- In 1998, he was elected Foreign Associate of the United States National Academy of Sciences.
- In 2000 he was appointed to the Order of Merit.
- In 2004 he was awarded the De Morgan Medal for his wide and original contributions to mathematical physics.
- In 2005 Penrose was awarded an honorary doctorate by Warsaw University and Katholieke Universiteit Leuven (Belgium), and in 2006 by the University of York.
- In 2008 Penrose was awarded the Copley Medal. He is also a Distinguished Supporter of Humanists UK and one of the patrons of the Oxford University Scientific Society.
- In 2011, Penrose was awarded the Fonseca Prize by the University of Santiago de Compostela.
- In 2012, Penrose was awarded the Richard R. Ernst Medal by ETH Zürich for his contributions to science and strengthening the connection between science and society.
- In 2015 Penrose was awarded an honorary doctorate by CINVESTAV-IPN (Mexico).

Steven Hawking

Steven Hawking was born in 1942 in Oxford, England. Despite financial difficulties, both his father. Frank Hawking and his mother, Isobel, attended Oxford University, with Frank studying medicine and Isobel philosophy. After Frank Hawking became the head of the division of parasitology for the National Institute of Medical Research, the family moved to St. Albans, where they were regarded as highly intelligent but eccentric. They lived in a large, cluttered, poorly-maintained house, and often ate meals in silence, with each family member reading a book at the table.

Steven Hawking entered University College Oxford in 1959 at the age of 17. His father had wished him to study medicine, but he chose physics. His study habits were bad, and he almost missed obtaining a first class degree. However, after an oral exam, he was awarded a "first", which he needed for a scholarship to Cambridge University.

At Cambridge, Steven Hawking was assigned to work with Dennis William Sciama, one of the founders of modern cosmology. Hawking found that his training in mathematics had not prepared him to work in the field of general relativity. Furthermore he was diagnosed

Figure 9.1: **Sir Roger Penrose (born in 1931).**

Figure 9.2: **Steven Hawking (1942-2018).**

with amyotrophic lateral sclerosis, a motor neuron disease and given only two years to live by his doctors. Not surprisingly, he fell into a depression, and wondered whether it was worthwhile to continue his studies.

However, at this time he met his future wife, Jane Wilde, and in 1964 the became engaged, although she was aware of his reduced life expectancy and physical limitations. Later they were married and had three children. This gave Steven Hawking something to live for, and his doctors' prognosis proved to be too pessimistic. He lived for another 50 years, longer than any other victim of the disease from which he suffered. He lost the use of his legs, and also a loss of speech, but was able to control a machine that synthesized speech by means a few cheek muscles that he could still use.

Despite these seemingly insurmountable handicaps, Steven Hawking had a distinguished scientific career. He ultimately rose to become the director of the Center for Theoretical Cosmology at the University of Cambridge. Between 1979 and 2009. he was also Lucasian Professor of Mathematics, a post once occupied by Sir Isaac Newton.

Among Hawking's many scientific achievements are gravitational singularity theorems, which he derived in collaboration with Roger Penrose. He also used the general theory of relativity to predict radiation emitted by black holes (Hawking radiation). Hawking's theories of cosmology united general relativity and quantum theory. He also had great success as an author of popular books about science.

The Penrose-Hawking singularity theorems

The Wikipedia article on these theorems states that:

The Penrose theorem guarantees that some sort of geodesic incompleteness occurs inside any black hole whenever matter satisfies reasonable energy conditions (It does not hold for matter described by a super-field, i.e., the Dirac field). The energy condition required for the black-hole singularity theorem is weak: it says that light rays are always focused together by gravity, never drawn apart, and this holds whenever the energy of matter is non-negative.

Hawking's singularity theorem is for the whole universe, and works backwards in time: it guarantees that the (classical) Big Bang has infinite density. This theorem is more restricted and only holds when matter obeys a stronger energy condition, called the dominant energy condition, in which the energy is larger than the pressure. All ordinary matter, with the exception of a vacuum expectation value of a scalar field, obeys this condition. During inflation, the universe violates the dominant energy condition, and it was initially argued (e.g. by Starobinsky) that inflationary cosmologies could avoid the initial big-bang singularity. However, it has since been shown that inflationary cosmologies are still past-incomplete, and thus require physics other than inflation to describe the past boundary of the inflating region of spacetime.

9.2 The Higgs boson

Some excerpts from Peter Higgs' biography

Peter Higgs was born in Newcastle upon Tyne in the UK, to a Scottish mother and an English father who worked as a sound engineer at the BBC. Because he suffered from asthma, Peter received part of his early education at his home in Bristol before moving to London to study math and physics at age 17. He received his Ph.D. from King's College in 1954. He then moved to the University of Edinburgh, where he has remained, with the exception of a few years spent in London in the late 1950s. Peter Higgs has two sons.

According to modern physics, matter consists of a set of particles that act as building blocks. Between these particles lie forces that are mediated by another set of particles. A fundamental property of the majority of particles is that they have a mass. Independently of one another, in 1964 both Peter Higgs and the team of Francois Englert and Robert Brout proposed a theory about the existence of a particle that explains why other particles have a mass. In 2012, two experiments conducted at the CERN laboratory confirmed the existence of the Higgs particle.

Peter Higgs... graduated with First Class Honours in Physics from King's College, University of London, in 1950. A year later, he was awarded an MSc

and started research, initially under the supervision of Charles Coulson and, subsequently, Christopher Longuet-Higgins. In 1954, he was awarded a PhD for a thesis entitled ‘Some Problems in the Theory of Molecular Vibrations’, work which signalled the start of his life-long interest in the application of the ideas of symmetry to physical systems.

In 1954, Peter Higgs moved to the University of Edinburgh for his second year as a Royal Commission for the Exhibition of 1851 Senior Student, and remained for a further year as a Senior Research Fellow. He returned to London in 1956 to take up an ICI Research Fellowship, spending a year at University College and a little over a year at Imperial College, before taking up an appointment as Temporary Lecturer in Mathematics at University College. In October 1960 Peter Higgs returned to Edinburgh, taking up a lectureship in Mathematical Physics at the Tait Institute. He was promoted to Reader in 1970, became a Fellow of the Royal Society of Edinburgh in 1974 and was promoted to a Personal Chair of Theoretical Physics in 1980. He was elected Fellow of the Royal Society in 1983 and Fellow of the Institute of Physics in 1991. He retired in 1996, becoming Professor Emeritus at the University of Edinburgh. He was awarded Fellowship of the University of Swansea in 2008, Honorary Membership of the Saltire Society and Fellowships of the Royal Scottish Society of the Arts and the Science Museum London in 2013.

Peter Higgs’ contribution to physics has been recognized by numerous academic honours: the Hughes Medal of the Royal Society (1981, shared with Tom Kibble), the Rutherford Medal of the Institute of Physics (1984, also shared with Tom Kibble), the Saltire Society & Royal Bank of Scotland Scottish Science Award (1990), the Royal Society of Edinburgh James Scott Prize Lectureship (1993), the Paul Dirac Medal and Prize of the Institute of Physics (1997), and the High Energy and Particle Physics Prize of the European Physical Society (1997, shared with Robert Brout and Francois Englert), the Royal Medal of the Royal Society of Edinburgh (2000), the Wolf Prize in Physics (2004, shared with Robert Brout and Francois Englert), the Stockholm Academy of Sciences Oskar Klein Memorial Lecture and Medal (2009) and the American Physical Society J. J. Sakurai Prize (2010), shared with Robert Brout, Francois Englert, Gerry Guralnik, Carl Hagen and Tom Kibble. He received a unique personal Higgs medal from the Royal Society of Edinburgh on 1 October 2012 and the 2013 Nonino Prize ‘Man of Our Time’. He shared the award of the 2013 Edinburgh International Science Festival Edinburgh Medal with CERN and the 2013 Prince of Asturias Award for Technical and Scientific Research with Francois Englert and CERN.

He has received honorary degrees from the Universities of Bristol (1997), Edinburgh (1998), Glasgow (2002), King’s College London (2009), University College London (2010), Cambridge (2012), Heriot-Watt (2012), Manchester, (2013), Durham (2013), La Scuola Internazionale Superiore di Studi Avantzi di Trieste (2013), St. Andrews (2014) and the Université Libre de Bruxelles.

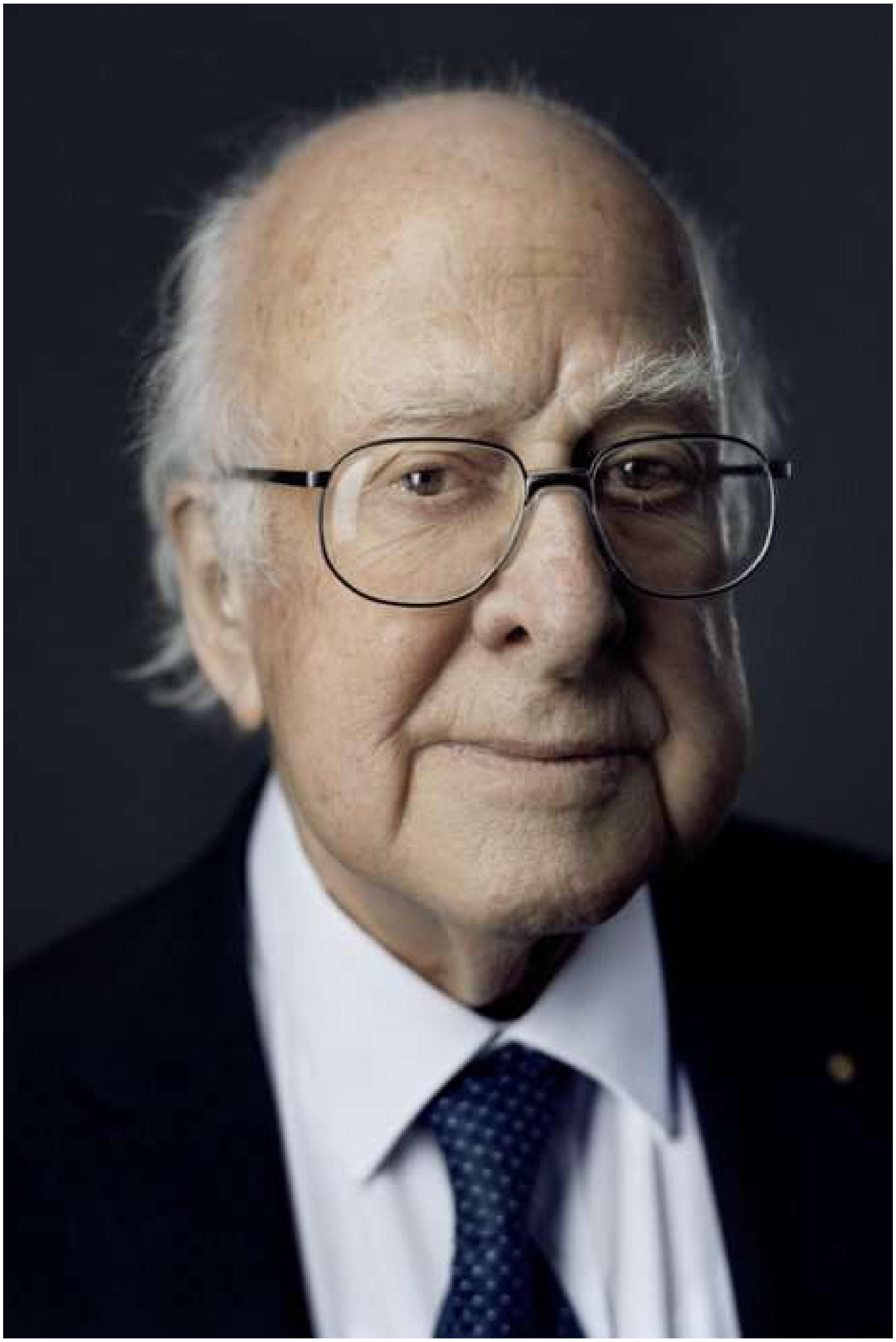

Figure 9.3: **Peter Higgs (born in 1929). He received the Nobel Prize in Physics in 2013, the year that the discovery of the Higgs boson was confirmed by CERN.**

Figure 9.4: **The enormous Large Hadron Collider (LHC) at CERN, Geneva, Switzerland. It lies in a tunnel 27 kilometres in circumference. On 14 March 2013, CERN announced confirmation that the 125 Gev/c^2 particle detected earlier with the LHC was indeed the long-saught Higgs Boson.**

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32. Sean Carroll (2013). *The Particle at the End of the Universe: How the Hunt for the Higgs Boson Leads Us to the Edge of a New World.* Dutton.
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Chapter 10

SPACE EXPLORATION

10.1 Astronautics

Rocket timeline from Wikipedia

- 11th century AD - The first documented record of gunpowder and the fire arrow, an early form of rocketry, appears in the Chinese text Wujing Zongyao.
- 1650 - Artis Magnae Artilleriae pars prima ("Great Art of Artillery, the First Part") is printed in Amsterdam, about a year before the death of its author, Kazimierz Siemienowicz.
- 1664 - A "space rocket" is imagined as a future technology to be studied in France and its drawing is ordered by French finance minister Colbert; designed by Le Brun on a Gobelins tapestry.
- 1798 - Tipu Sultan, the King of the state of Mysore in India, develops and uses iron rockets against the British Army.
- 1801 - The British Army develops the Congreve rocket based on weapons used against them by Tipu Sultan.
- 1806 - Claude Ruggieri, an Italian living in France, launched animals on rockets and recovered them using parachutes. He was prevented from launching a child by police.
- 1813 - "A Treatise on the Motion of Rockets" by William Moore - first appearance of the rocket equation.
- 1818 - Henry Trengrouse demonstrates his rocket apparatus for projecting a lifeline from a wrecked ship to the shore, later widely adopted.
- 1844 - William Hale invents the spin-stabilized rocket
- 1861 - William Leitch publishes an essay "A Journey Through Space" as a humorous science fantasy story about a space gun launching a manned spacecraft equipped with rockets for landing on the Moon, but eventually used for another orbital maneuver.

Figure 10.1: **A jet-driven steam engine invented by Hero of Alexandria in the 1st century A.D..**

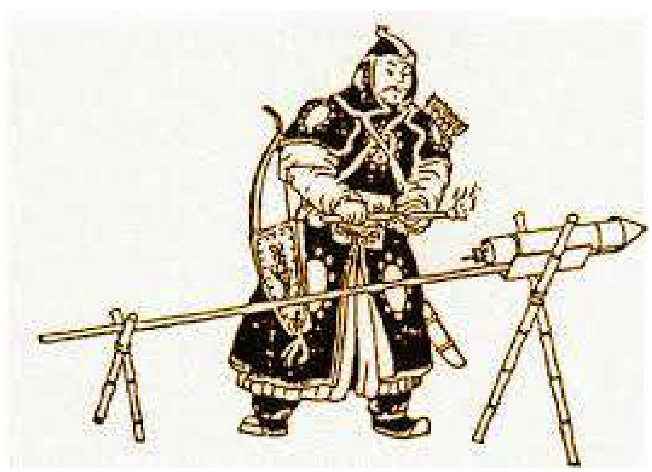

Figure 10.2: **Rockets were used in warfare in China in the 11th century.**

Figure 10.3: **Congreve rockets were used in the bombardment of Copenhagen in 1807. It was a terror attack on the civilian population, carried out although no state of war existed between Denmark and England.**

Figure 10.4: **The Nazi V2 rocket, which launched the space age, was also used for the terror bombardment of civilians.**

- 1902 - French cinema pioneer Georges Méliés directs A Trip to the Moon, the first film about space travel.
- 1903 - Konstantin Tsiolkovsky begins a series of papers discussing the use of rocketry to reach outer space, space suits, and colonization of the Solar System. Two key points discussed in his works are liquid fuels and staging.
- 1913 - Without knowing the work of Russian mathematician Konstantin Tsiolkovsky, French engineer Robert Esnault-Pelterie derived the equations for space flight, produced a paper that presented the rocket equation and calculated the energies required to reach the Moon and nearby planets.
- 1916 - first use of rockets (with the solid fuel Le Prieur rocket) for both air-to-air attacks, and air to ground.
- 1922 - Hermann Oberth publishes his scientific work about rocketry and space exploration: Die Rakete zu den Planetenräumen ("By Rocket into Planetary Space").
- 1924 - Society for Studies of Interplanetary Travel founded in Moscow by Konstantin Tsiolkovsky, Friedrich Zander and 200 other space and rocket experts
- 1926 - Robert Goddard launches the first liquid fuel rocket. This is considered by some to be the start of the Space Age.
- 1927 - Verein fÃ¼r Raumschiffahrt (VfR - "Spaceflight Society") founded in Germany.
- 1929 - Woman in the Moon, considered to be one of the first "serious" science fiction films.
- 1931 - Friedrich Schmiedl attempts the first rocket mail service in Austria
- 1933 - Sergei Korolev and Mikhail Tikhonravov launch the first liquid-fueled rocket in the Soviet Union.
- 1935 - Emilio Herrera Linares from Spain designed and made the first full-pressured astronaut suit, called the escafandra estratonáutica. The Russians then used a model of Herrera's suit when first flying into space of which the Americans would then later adopt when creating their own space program.
- 1936 - Research on rockets begins at the Guggenheim Aeronautical Laboratory at the California Institute of Technology (GALCIT), the predecessor to the Jet Propulsion Laboratory, under the direction of Frank Malina and Theodore von KármÃ¡n.
- 1937 - Peenemünde Army Research Center founded in Germany.
- 1938 - The Projectile Development Establishment founded at Fort Halstead for the United Kingdom's research into military solid-fuel rockets.
- 1939 - Katyusha multiple rocket launchers are a type of rocket artillery first built and fielded by the Soviet Union.

- **1941 - French rocket EA-41 is launched, being the first European liquid propellant working rocket[8](It was, however, preceded by the Peenemunde A5 and Soviet experiments.)**
- **1941 - Jet Assisted Take Off JATO installed on US Army Air Corp Ercoupe aircraft occurred on 12 August in March Field, California.**
- **1942 - Wernher von Braun and Walter Dornberger launch the first V-2 rocket at Peenemünde in northern Germany.**
- **1942 - A V-2 rocket reaches an altitude of 85 km.**
- **1944 - The V-2 rocket MW 18014 reaches an altitude of 176 km, becoming the first man-made object in space.**
- **1945 - Lothar Sieber dies after the first vertical take-off manned rocket flight in a Bachem Ba 349 "Natter".**
- **1945 - Operation Paperclip takes 1,600 German rocket scientists and technicians to the United States.**
- **1945 - Operation Osoaviakhim takes 2,000 German rocket scientists and technicians to the Soviet Union.**
- **1946 - First flight of the Nike missile, later the first operational surface-to-air guided missile.**
- **1947 - Chuck Yeager achieves the first manned supersonic flight in a Bell X-1 rocket-powered aircraft.**
- **1949 - Willy Ley publishes The Conquest of Space.**
- **1952 - 22 May, French Véronique 1 rocket is launched from the Algerian desert.**
- **1952 - Wernher von Braun discusses the technical details of a manned exploration of Mars in Das Marsprojekt.**
- **1953 - Colliers magazine publishes a series of articles on man's future in space, igniting the interest of people around the world. The series includes numerous articles by Ley and von Braun, illustrated by Chesley Bonestell.**
- **1956 - First launch of PGM-17 Thor, the first US ballistic missile and forerunner of the Delta space launch rockets.**
- **1957 - Launch of the first ICBM, the USSR's R-7 (8K71), known to NATO as the SS-6 Sapwood.**
- **1957 - The USSR launches Sputnik 1, the first artificial satellite.**
- **1958 - The U.S. launches Explorer 1, the first American artificial satellite, on a Jupiter-C rocket.**
- **1958 - US launches their first ICBM, the Atlas-B (the Atlas-A was a test article only).**
- **1961 - the USSR launches Vostok 1, Yuri Gagarin reached a height of 327 km above Earth and was the first man to orbit Earth.**
- **1961 - US, a Mercury capsule named Freedom 7 with Alan B. Shepard, spacecraft was launched by a Redstone rocket on a ballistic trajectory suborbital flight. It was the first human space mission that landed with pilot still in spacecraft, thus the first complete human spaceflight by FAI definitions.**

- **1962 - The US launches Mercury MA-6 (Friendship 7) on an Atlas D booster, John Glenn puts America in orbit.**
- **1963 - The USSR launches Vostok 6, Valentina Tereshkova was the first woman (and first civilian) to orbit Earth. She remained in space for nearly three days and orbited the Earth 48 times.**
- **1963 - US X-15 rocket-plane, the first reusable manned spacecraft (suborbital) reaches space, pioneering reusability, carried launch and glide landings.**
- **1965 - USSR Proton rocket, highly successful launch vehicle with notable payloads, Salyut 6 and Salyut 7, Mir, and ISS components.**
- **1965 - Robert Salked investigates various single stage to orbit spaceplane concepts.**
- **1966 - USSR Luna 9, the first soft landing on the Moon.**
- **1966 - USSR launches Soyuz spacecraft, longest-running series of spacecraft, eventually serving Soviet, Russian and International space missions.**
- **1968 - USSR Zond 5, two tortoises and smaller biological Earthlings circle the Moon and return safely to Earth.**
- **1968 - US Apollo 8, the first men to reach and orbit the Moon.**
- **1969 - US Apollo 11, first men on the Moon, first lunar surface extravehicular activity.**
- **1981 - US Space Shuttle pioneers reusability and glide landings.**
- **1998 - US Deep Space 1 is first deep space mission to use an ion thruster for propulsion.**
- **1998 - Russia launch Zarya module which is the first part of the International Space Station.**
- **2001 - Russian Soyuz spacecraft sent the first space tourist Dennis Tito to International Space Station.**
- **2004 - US-based, first privately developed, manned (suborbital) spaceflight, SpaceShipOne demonstrates reusability.**
- **2008 - SpaceX - with their Falcon 1 rocket - became the first private entity to successfully launch a rocket into orbit.**
- **2012 - The SpaceX Dragon space capsule - launched aboard a Falcon 9 launch vehicle - was the first private spacecraft to successfully dock with another spacecraft, and was also the first private capsule to dock at the International Space Station.**
- **2014 - First booster rocket returning from an orbital trajectory to achieve a zero-velocity-at-zero-altitude propulsive vertical landing. The first-stage booster of Falcon 9 Flight 9 made the first successful controlled ocean soft touchdown of a liquid-rocket-engine orbital booster on April 18, 2014.**
- **2015 - SpaceX's Falcon 9 Flight 20 was the first time that the first stage of an orbital rocket made a successful return and vertical landing.**
- **2017 - SpaceX's Falcon 9 SES-10 was the first time a used orbital rocket made a successful return.**

Figure 10.5: **Cosmonaut Yuri Gagarin (1934-1968) was the first man in space. On 12 April, 1961, his space capsule, Vostok 1, completed an orbit of the Earth. Gagarin became an international celebrity, and was awarded many honors and medals. He died in the crash of a routine MIG-15UTI training flight.**

10.2 Exploration of the Earth's Moon

In ancient times, the Greek philosopher Anaxagoras, who died in 428 BC, believed the Moon to be a giant spherical rock that reflects the light of the sun. This non-religious view of the heavens caused Anaxagoras to be persecuted and banished.

Aristarchus of Samos (c.310-c.230 BC), calculated the size of the Moon and its distance from the Earth (by observing the shadow of the Earth on the Moon during an eclipse, and the angles involved). He also calculated the distance from the Earth to the Sun. The values that he obtained were not very accurate, but they showed the Sun to be enormous in size in relation to the Earth and the Moon. As a result of his calculations he became the first person to suggest a sun-centered model for the solar system.

In our own era, the Soviet Union was the first to send a rocket to the Moon, the unmanned rocket Luna 2. which made a hard landing in September, 1959. Another Soviet rocket, Luna 3, photographed the far side of the moon in October of the same year.

These and other Soviet successes initiated a "space race" between the United States and the Soviet Union, and caused President John F. Kennedy to say to Congress, "...I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth. No single space project in this period will be more impressive to mankind, or more important in the long-range exploration of space; and none will be so difficult or expensive to accomplish."

In December, 1968, the crew of Apollo 8 became the first humans to enter a lunar orbit and to see the far side of the Moon. This success was followed by Apollo 11, in July, 1969, a manned spacecraft that made a soft landing on the Moon. Niel Armstrong, the commander of the mission, became, famously, the first human to set foot on the Moon.

In 1970, the first lunar robot vehicle landed on the Moon. It was sent by the Soviet Union and called "Lunokhod 1".

The manned Apollo missions were eventually abandoned by the United States, but the National Aeronautics and Space Administration (NASA) has continued to send missions to photograph the Moon. Some of the photographs are shown below.

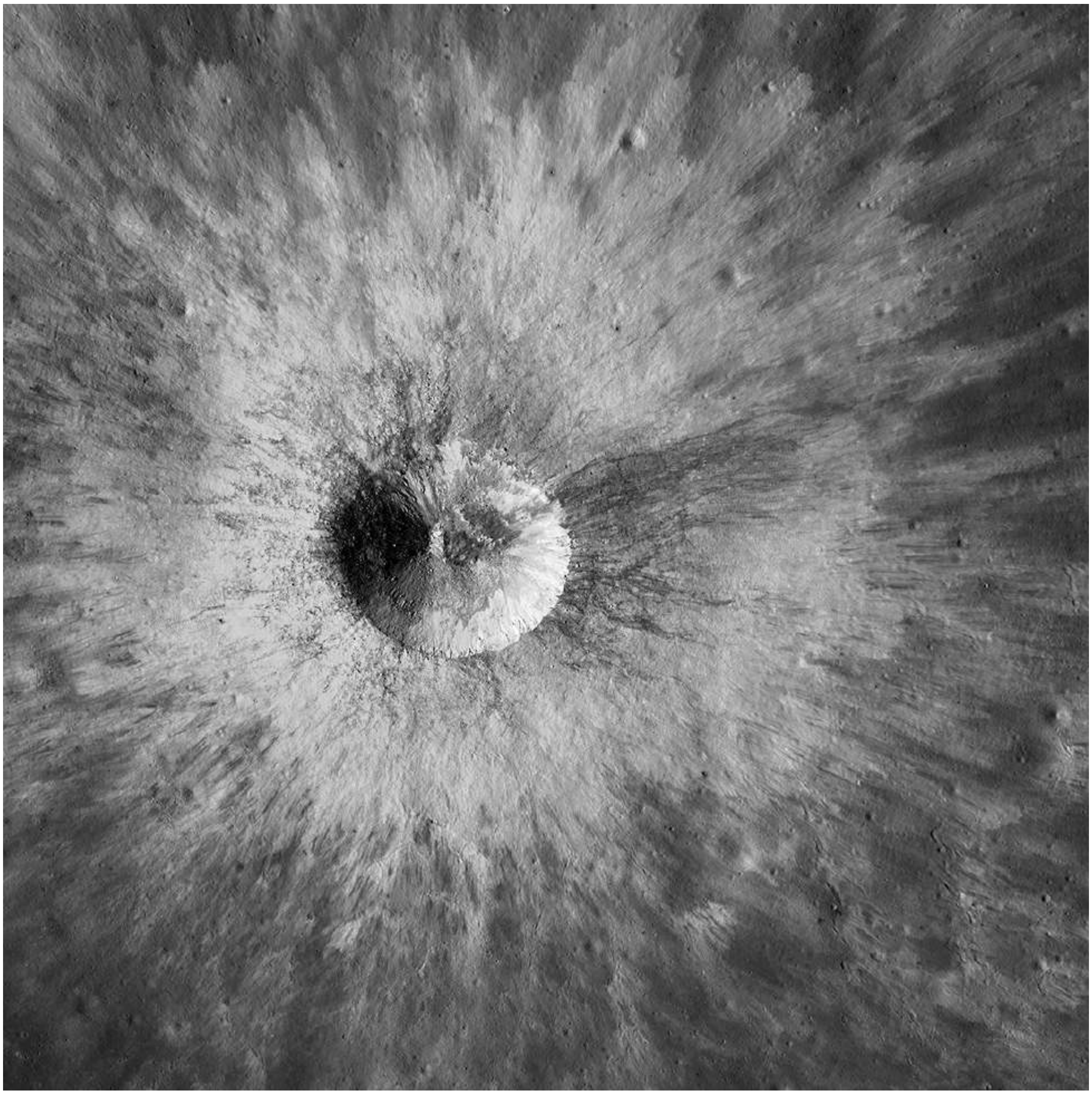

Figure 10.6: **A young ray impact crater blasted in the eroded wall of the partly buried crater Hedin. It is distant from the starkly beautiful landscape Armstrong saw: the Apollo 11 landing site on Mare Tranquillitatis is more than 1000 kilometers to the east (NASA/GSFC/Arizona State University, November 3, 2018).**

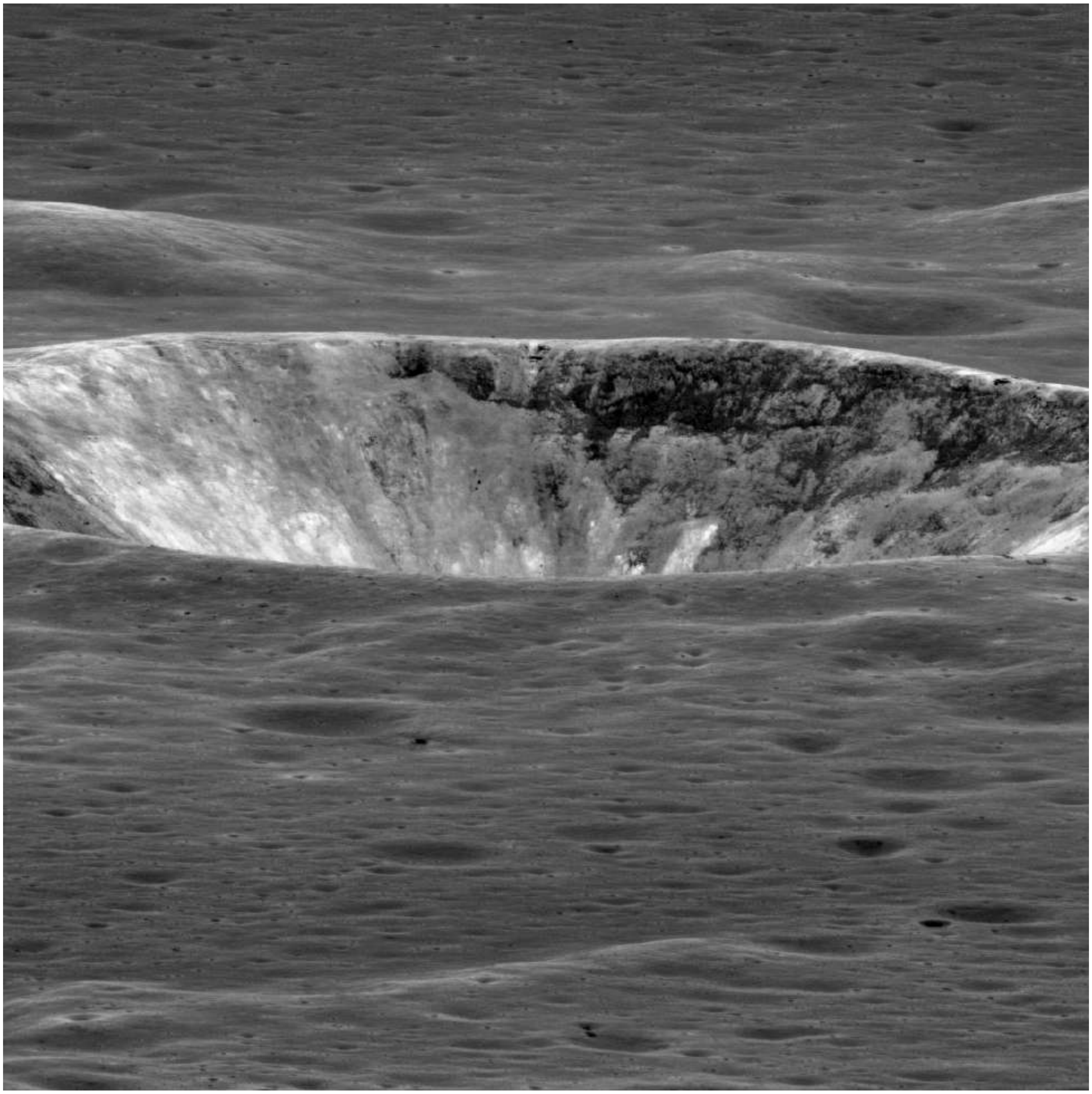

Figure 10.7: **This spectacular view across the rim of the Moon's Wallach crater, 3.5 miles (5700 meters) across, comes from NASA's Lunar Reconnaissance Orbiter. It was taken when the spacecraft was just 58 miles (93 kilometers) above the surface (NASA/GSFC/Arizona State University, September 17, 2018).**

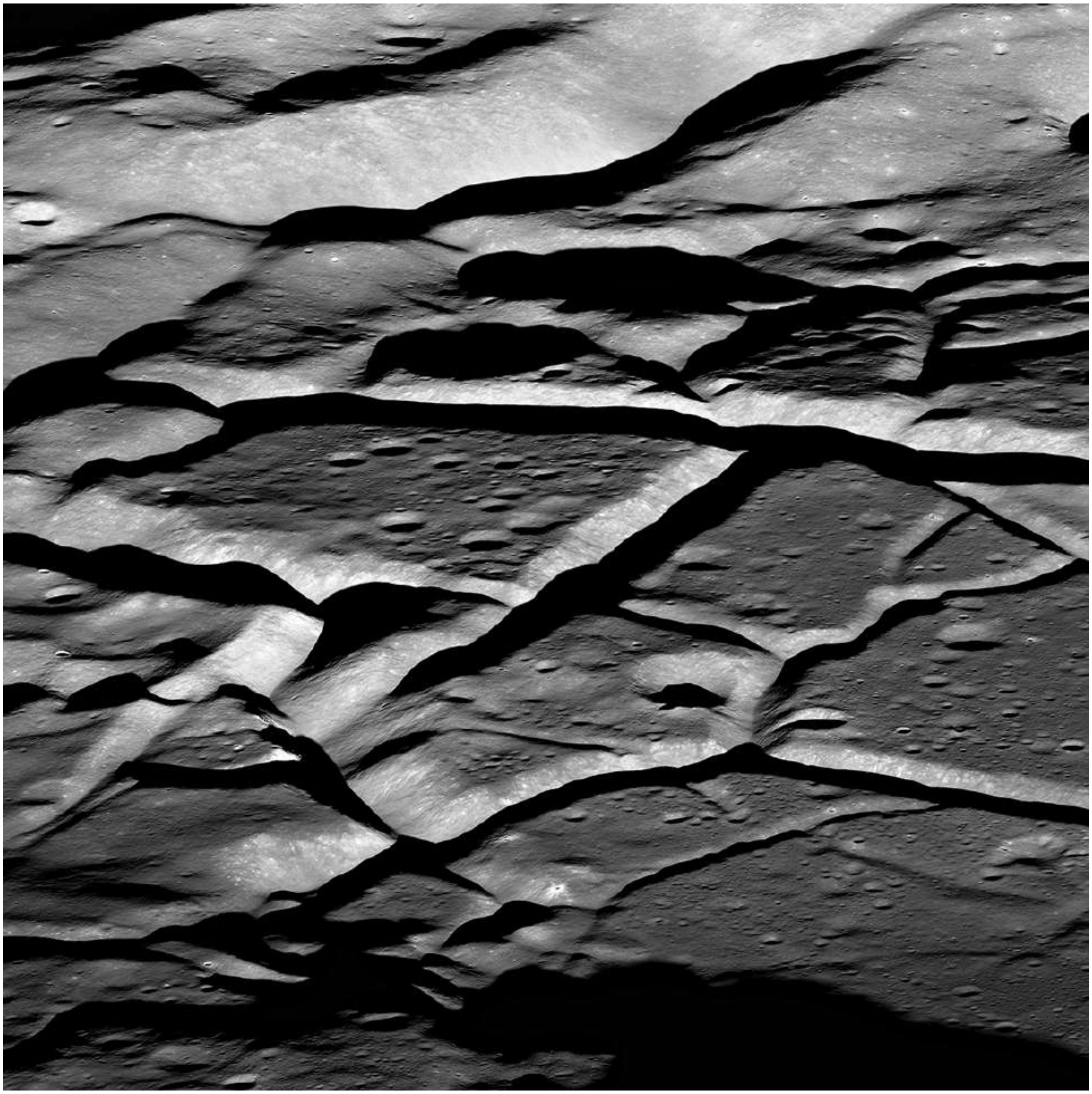

Figure 10.8: **NASA's Lunar Reconnaissance Orbiter captured this detailed look at the floor of Komarov crater on the far side of the Moon. The spectacular fractures that cut across the floor of Komarov, which is about 53 miles (85 kilometers) in diameter, were formed when magma rose from the mantle, uplifting and fracturing the crater in the process. In this case, the magma did not erupt to the surface, so the fractures remain visible. This image shows an area just over 9 miles (15 kilometers) wide (NASA/GSFC/Arizona State University, November 17, 2018).**

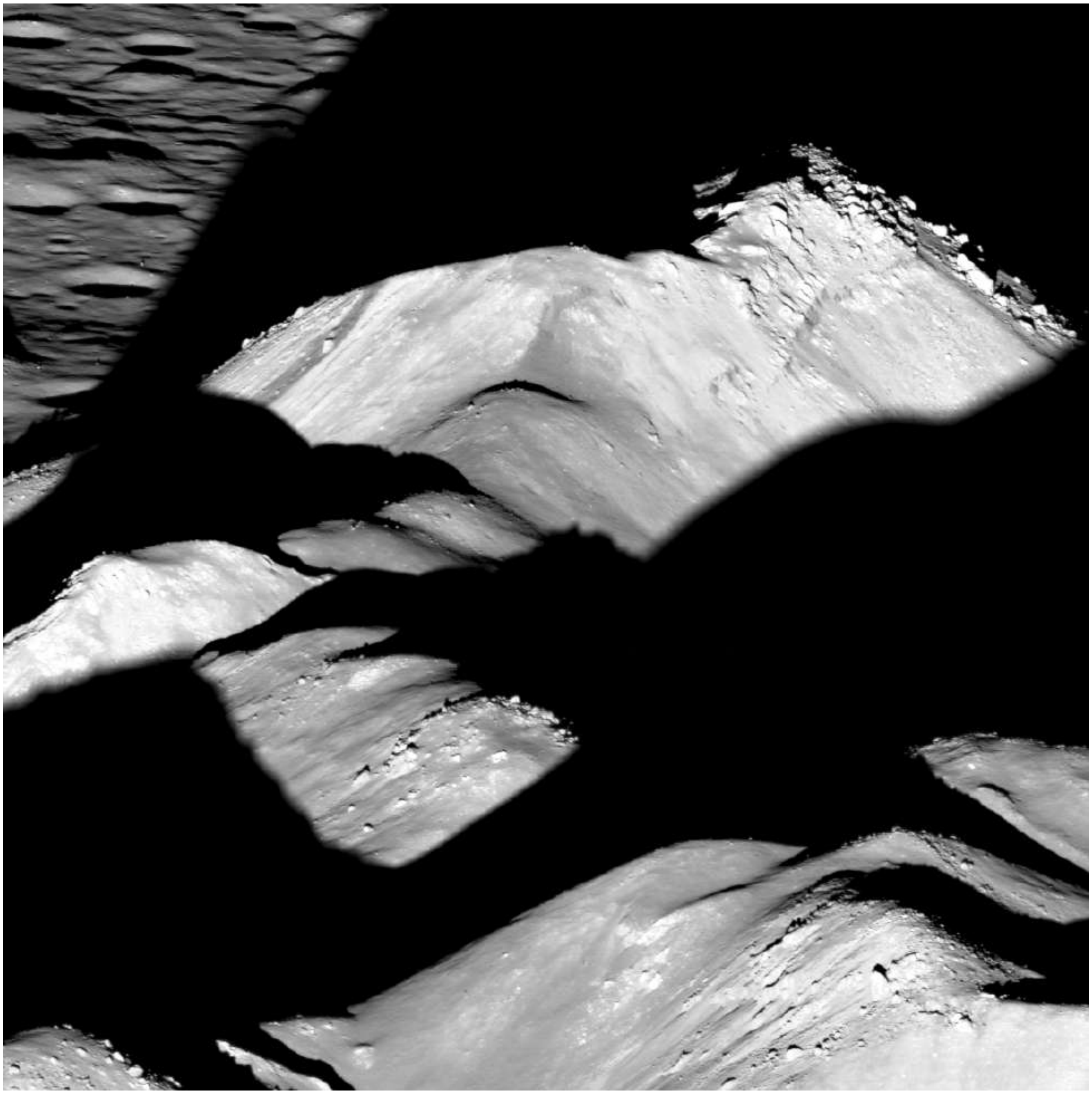

Figure 10.9: **The central peak in the Moon's Copernicus crater reveals the complexity of the lunar crust through distinct layering and patchy surface brightness. The area shown here is about 1.8 miles (3 kilometers) wide. Copernicus, which is easily seen with a moderately powerful backyard telescope, is one of the best-known craters on the Moon. Despite its age (around 860 million years), it is well preserved, with over 2.5 miles (4000 meters) of relief from floor to rim, and the tallest of its central peaks rises nearly a mile (approximately 1300 meters) above the crater floor. This image, centered on the central peaks, was captured just after dawn by NASA's Lunar Reconnaissance Orbiter (NASA/GSFC/Arizona State University, October 8, 2018).**

10.3 Missions to Mars

Below we list a few of the many missions to Mars:

- **Mars 4NM and Mars 5NM - projects intended by the Soviet Union for heavy Marsokhod (in 1973 according to initial plan of 1970) and Mars sample return (planned for 1975). The missions were to be launched on the failed N1 rocket.**
- **Mars 5M (Mars-79) - double-launching Soviet sample return mission planned to 1979 but cancelled due to complexity and technical problems**
- **Voyager-Mars - USA, 1970s - Two orbiters and two landers, launched by a single Saturn V rocket.**
- **Vesta - the multiaimed Soviet mission, developed in cooperation with European countries for realisation in 1991-1994 but canceled due to the Soviet Union disbanding, included the flyby of Mars with delivering the aerostat and small landers or penetrators followed by flybys of 1 Ceres or 4 Vesta and some other asteroids with impact of penetrator on the one of them.**
- **Mars Aerostat - Russian/French balloon part for cancelled Vesta mission and then for failed Mars 96 mission,[71] originally planned for the 1992 launch window, postponed to 1994 and then to 1996 before being cancelled.**
- **Mars Together, combined U.S. and Russian mission study in the 1990s. To be launched by a Molinya with possible U.S. orbiter or lander.**
- **Mars Environmental Survey - set of 16 landers planned for 1999-2009**
- **Mars-98 - Russian mission including an orbiter, lander, and rover, planned for 1998 launch opportunity as repeat of failured Mars 96 mission and cancelled due to lack of funding.**
- **Mars Surveyor 2001 Lander - October 2001 - Mars lander (refurbished, became Phoenix lander)**
- **Kitty Hawk - Mars airplane micromission, proposed for December 17, 2003, the centennial of the Wright brothers' first flight. Its funding was eventually given to the 2003 Mars Network project.[76]**
- **NetLander - 2007 or 2009 - Mars netlanders**
- **Beagle 3 - 2009 British lander mission meant to search for life, past or present.**
- **Mars Telecommunications Orbiter - September 2009 - Mars orbiter for telecommunications**
- **Sky-Sailor - 2014 - Plane developed by Switzerland to take detailed pictures of Mars surface**
- **Mars Astrobiology Explorer-Cacher - 2018 rover concept, cancelled due to budget cuts in 2011. Sample cache goal later moved to Mars 2020 rover.**

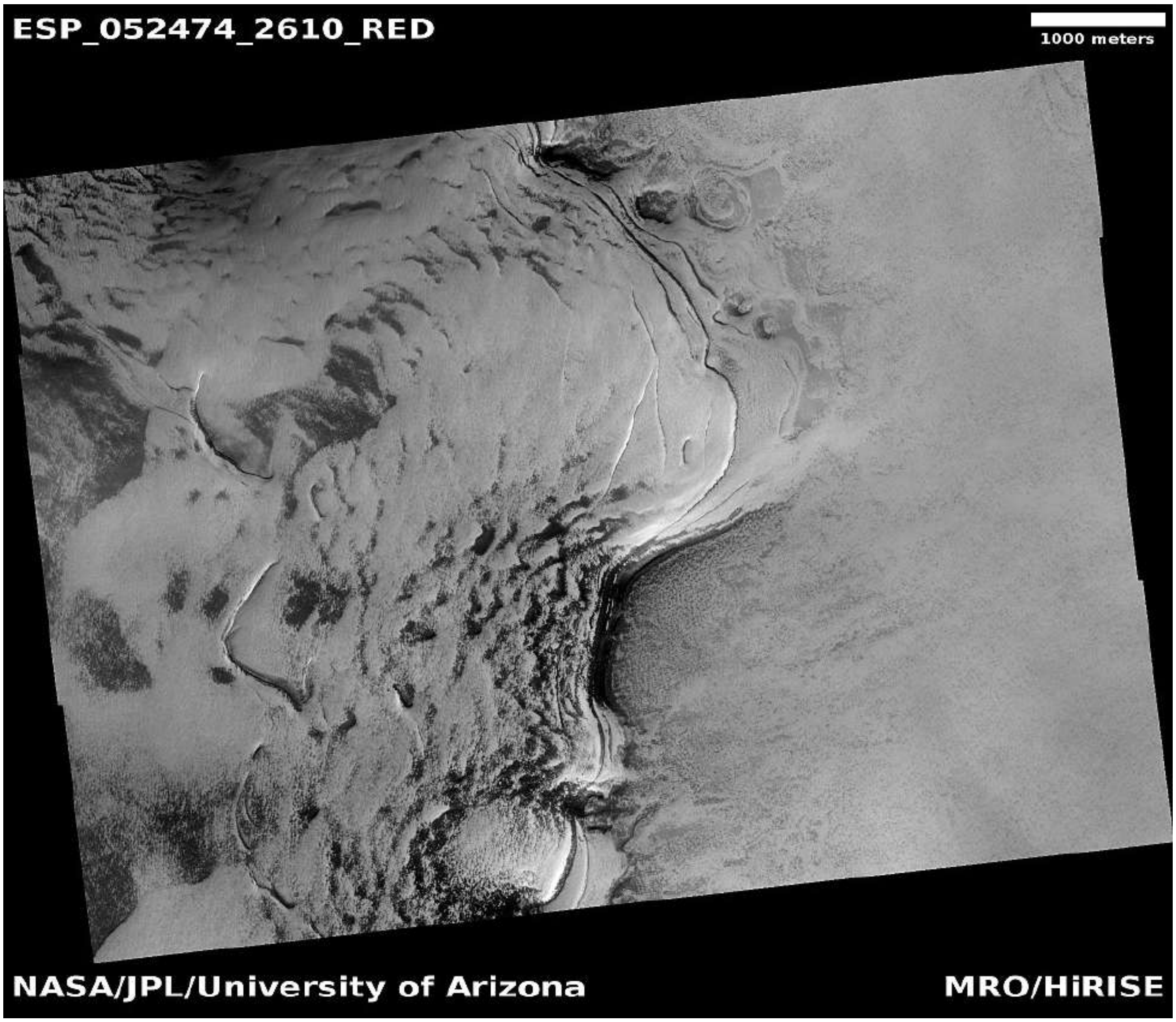

Figure 10.10: **Ridges in Mare Boreum quadrangle, as seen by HiRISE under HiWish program.**

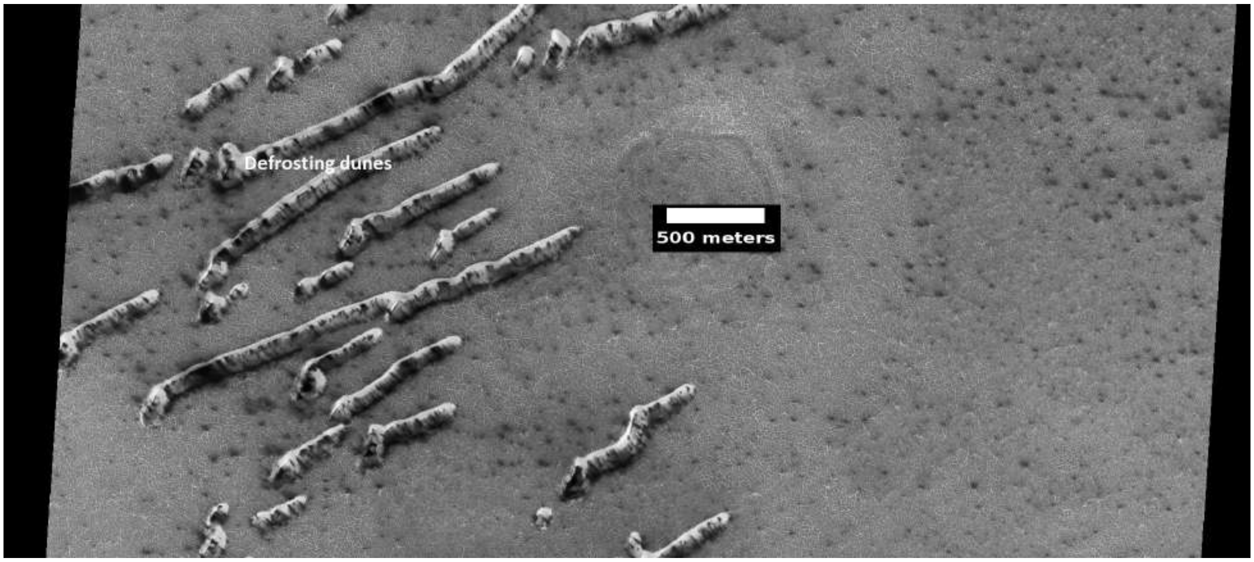

Figure 10.11: **Defrosting dunes and ice in troughs of polygons, as seen by hirise under HiWish program (Mare Borium).**

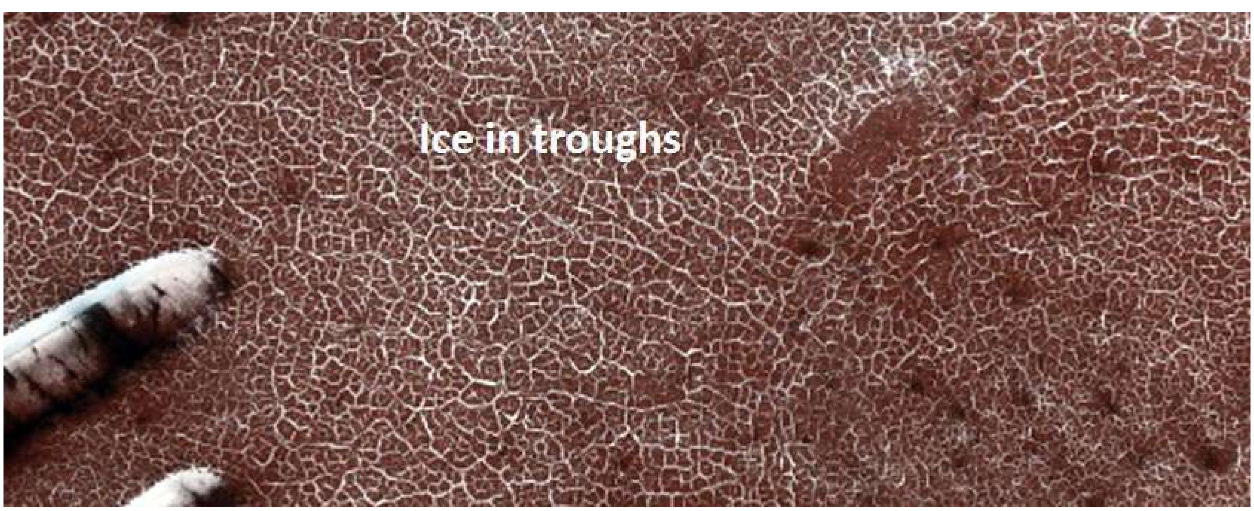

Figure 10.12: **Defrosting dunes and ice in troughs of polygons, as seen by hirise under HiWish program, in color.**

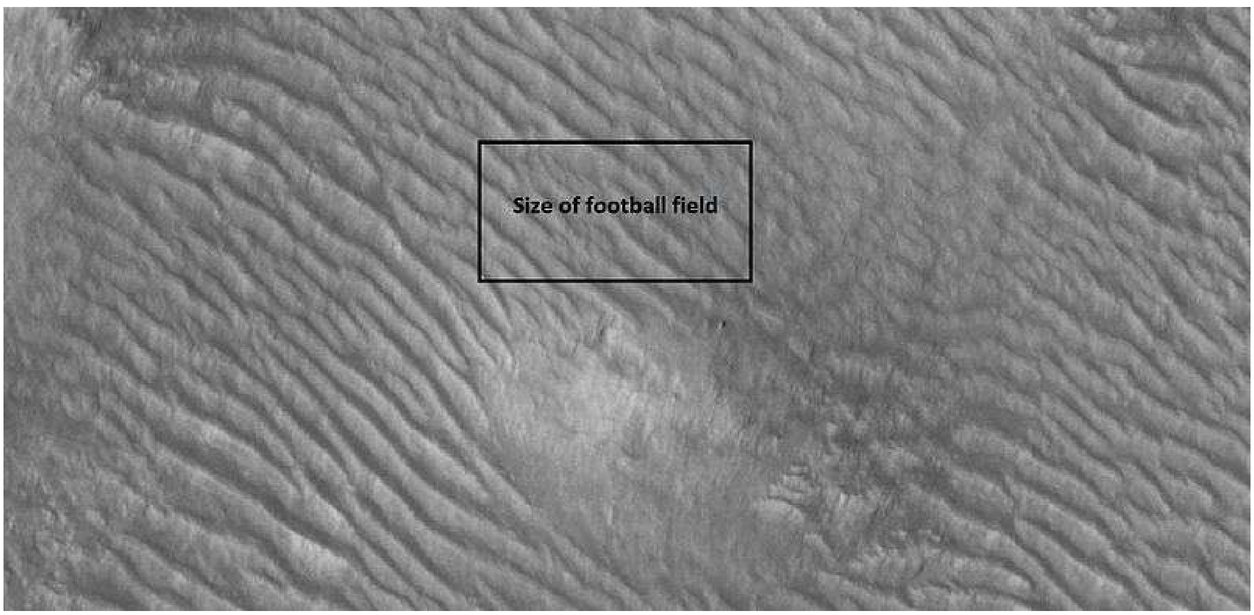

Figure 10.13: **Close-up of ridges on crater floor, as seen by hirise under HiWish program. Location is 33.592 N and 219.564 E (Diacria quadangle).**

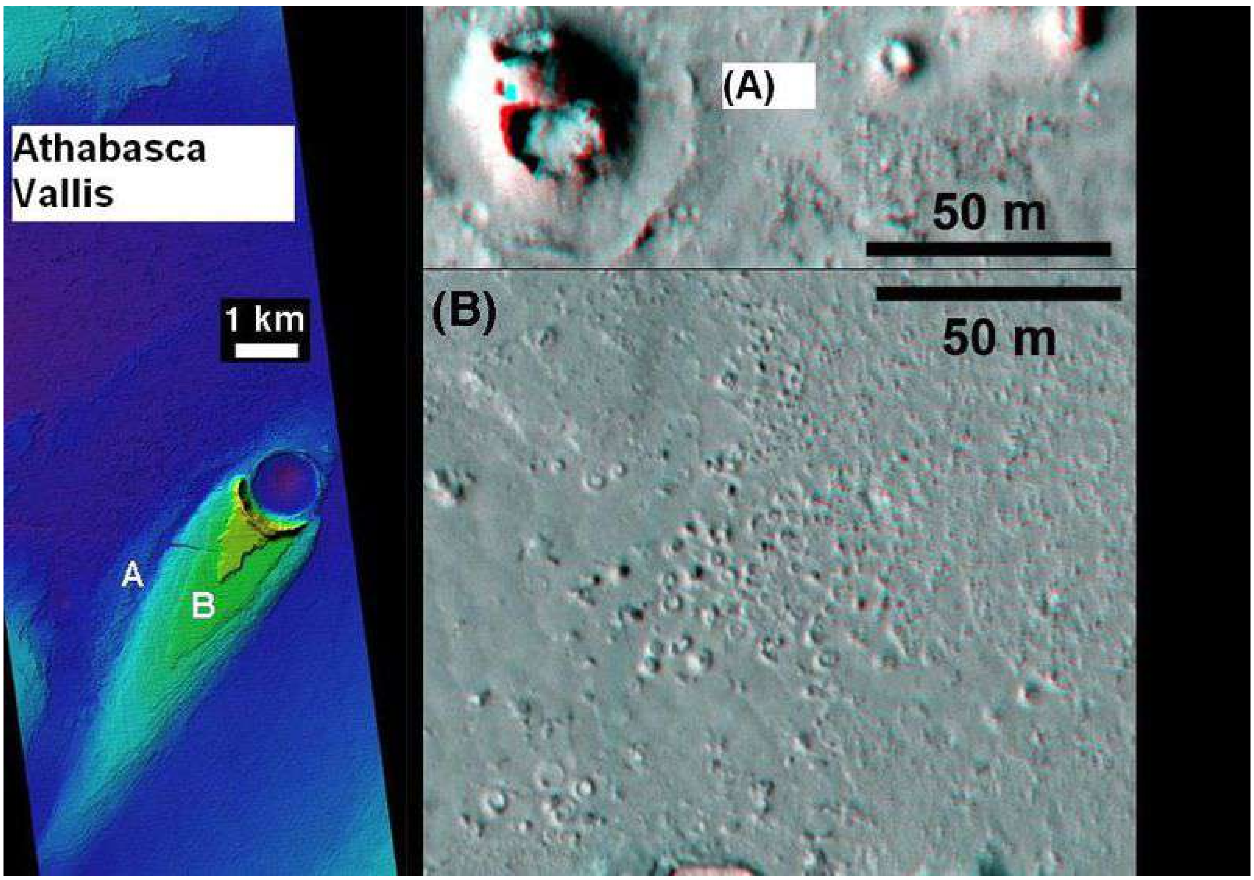

Figure 10.14: **Cones in Athabasca Vallis, Elysium quadrangle, as seen by HiRISE. Cones were formed from lava interacting with ice. Larger cones in upper image were produced when water/steam forced its way through thicker layer of lava. Difference between highest elevation (red) to lowest (dark blue) is 170 m (560 ft).**

10.4 The Cassini-Huygens space probe

The Wikipedia article on Cassini-Huygens gives the following description of the probe:

The Cassini-Huygens space-research mission, commonly called Cassini, involved a collaboration between NASA, the European Space Agency (ESA), and the Italian Space Agency (ASI) to send a probe to study the planet Saturn and its system, including its rings and natural satellites. The Flagship-class robotic spacecraft comprised both NASA's Cassini probe and ESA's Huygens lander, which landed on Saturn's largest moon, Titan.Cassini was the fourth space probe to visit Saturn and the first to enter its orbit. The two craft took their names from the astronomers Giovanni Cassini and Christiaan Huygens.

Launched aboard a Titan IVB/Centaur on October 15, 1997, Cassini was active in space for nearly 20 years, with 13 years spent orbiting Saturn and studying the planet and its system after entering orbit on July 1, 2004. The voyage to Saturn included flybys of Venus (April 1998 and July 1999), Earth (August 1999), the asteroid 2685 Masursky, and Jupiter (December 2000). The mission ended on September 15, 2017, when Cassini's trajectory took it into Saturn's upper atmosphere and it burned up in order to prevent any risk of contaminating Saturn's moons, which might have offered habitable environments to stowaway terrestrial microbes on the spacecraft. The mission is widely perceived to have been successful beyond expectations. NASA's Planetary Science Division Director, Jim Green, described Cassini-Huygens as a "mission of firsts", that has revolutionized human understanding of the Saturn system, including its moons and rings, and our understanding of where life might be found in the Solar System.

Cassini's planners originally scheduled a mission of four years, from June 2004 to May 2008. The mission was extended for another two years until September 2010, branded the Cassini Equinox Mission. The mission was extended a second and final time with the Cassini Solstice Mission, lasting another seven years until September 15, 2017, on which date Cassini was de-orbited to burn up in Saturn's upper atmosphere.

The Huygens module traveled with Cassini until its separation from the probe on December 25, 2004; it landed by parachute on Titan on January 14, 2005. It returned data to Earth for around 90 minutes, using the orbiter as a relay. This was the first landing ever accomplished in the outer Solar System and the first landing on a moon other than Earth's Moon.

At the end of its mission, the Cassini spacecraft executed its "Grand Finale": a number of risky passes through the gaps between Saturn and Saturn's inner rings. This phase aimed to maximize Cassini's scientific outcome before the spacecraft was disposed. The atmospheric entry of Cassini ended the mission, but analyses of the returned data will continue for many years.

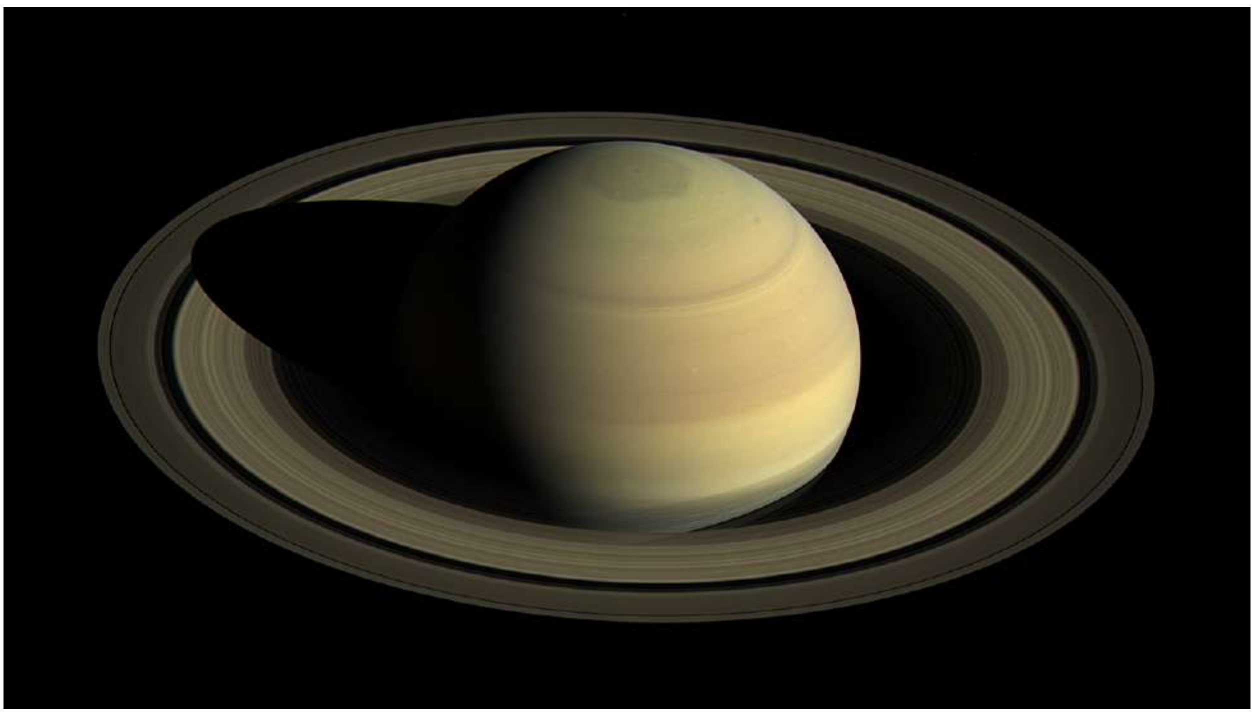

Figure 10.15: **This view shows Saturn's northern hemisphere in 2016, as that part of the planet nears its northern hemisphere summer solstice in May 2017.**

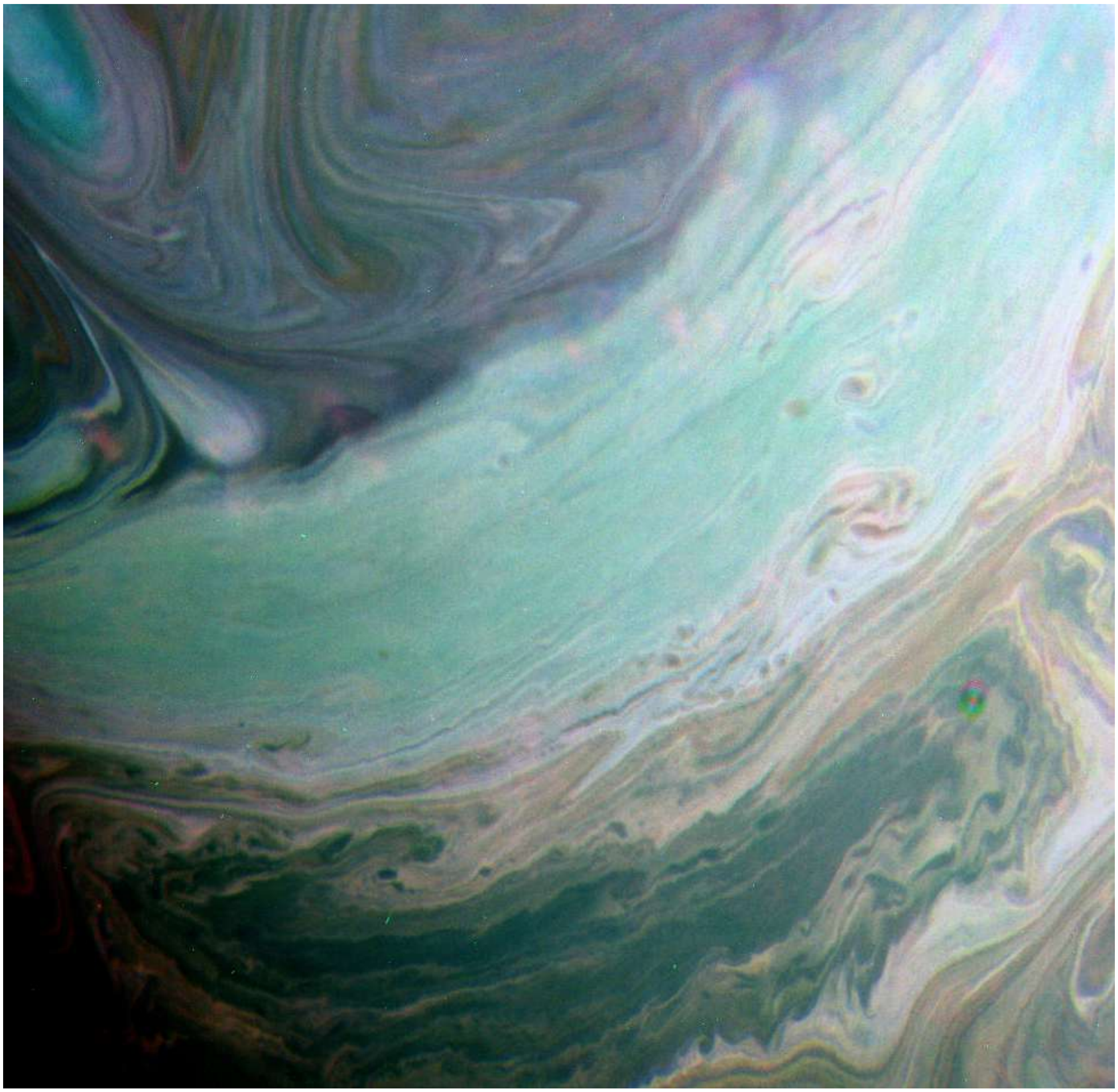

Figure 10.16: **Amateur Image: Saturn in the Infrared: A false-color view of Saturn's clouds from Kevin M. Gill, a frequent amateur processor of space images.**

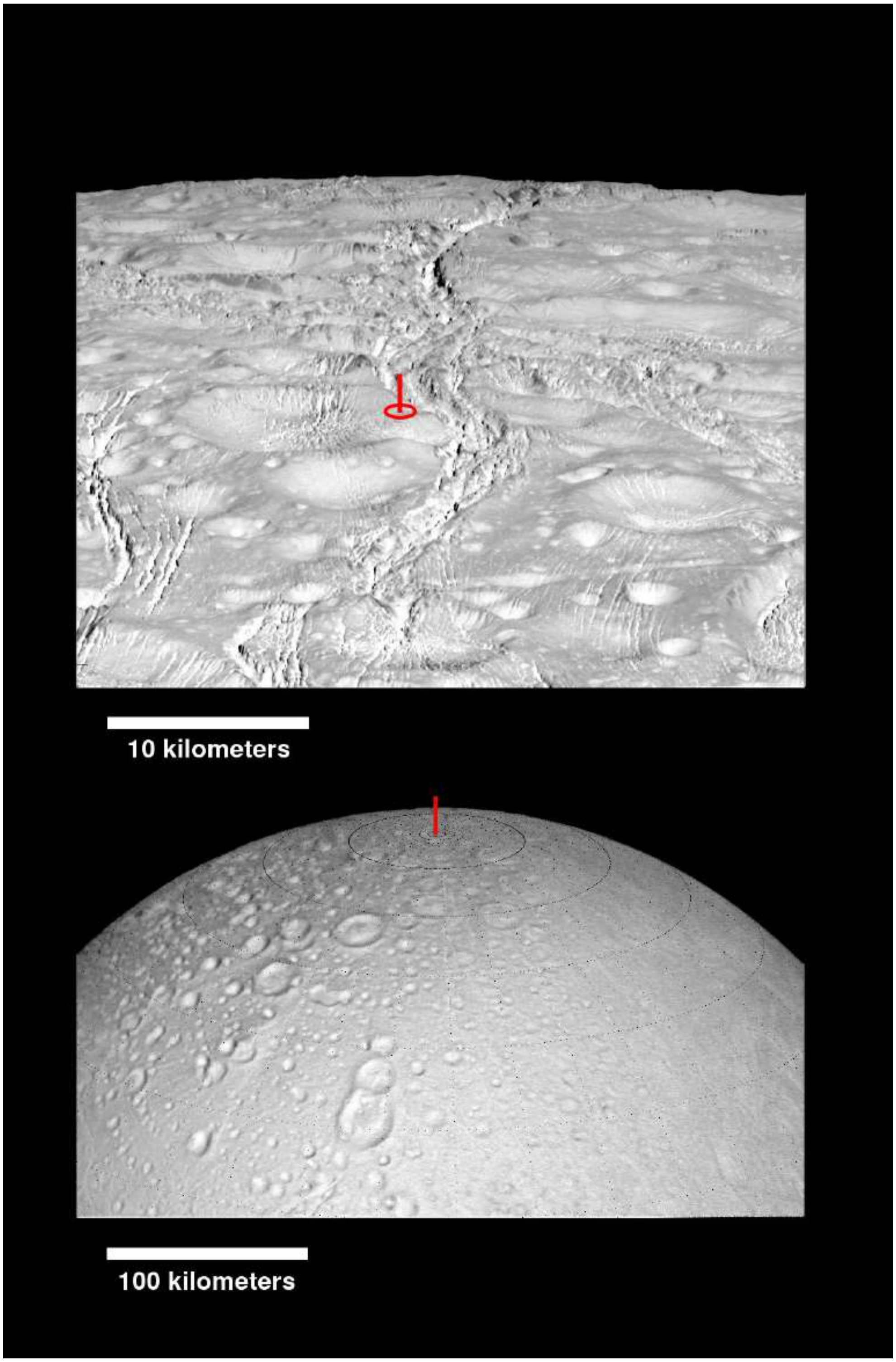

Figure 10.17: **This montage of images shows the precise location of the north pole on Saturn's icy moon Enceladus. The snow-white surface is kept bright by material sprayed from the active plume of ice and vapor in the moon's south polar region.**

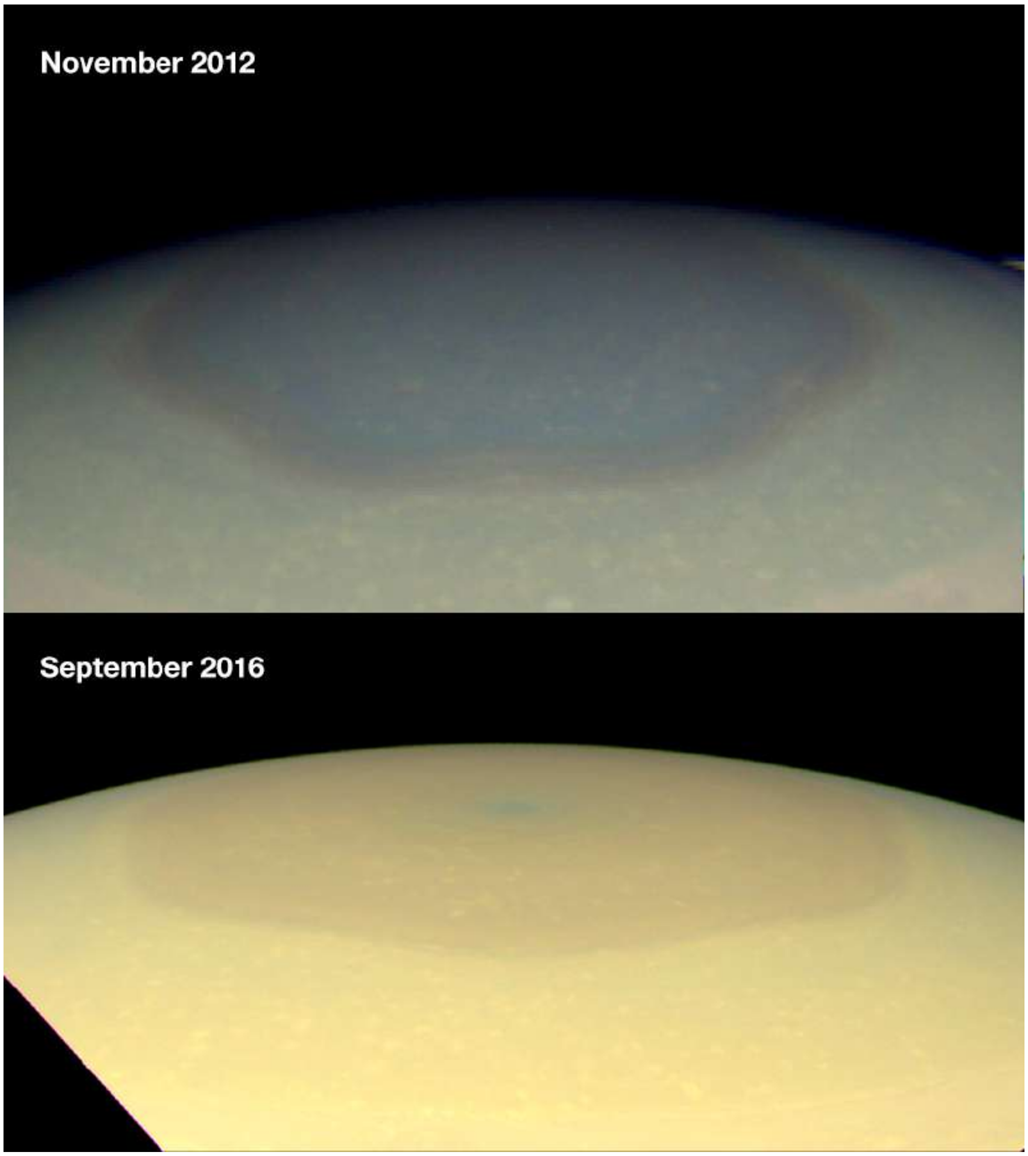

Figure 10.18: **Changing Colors in Saturn's North: These two natural color images from Cassini show the changing appearance of Saturn's north polar region between 2012 and 2016.**

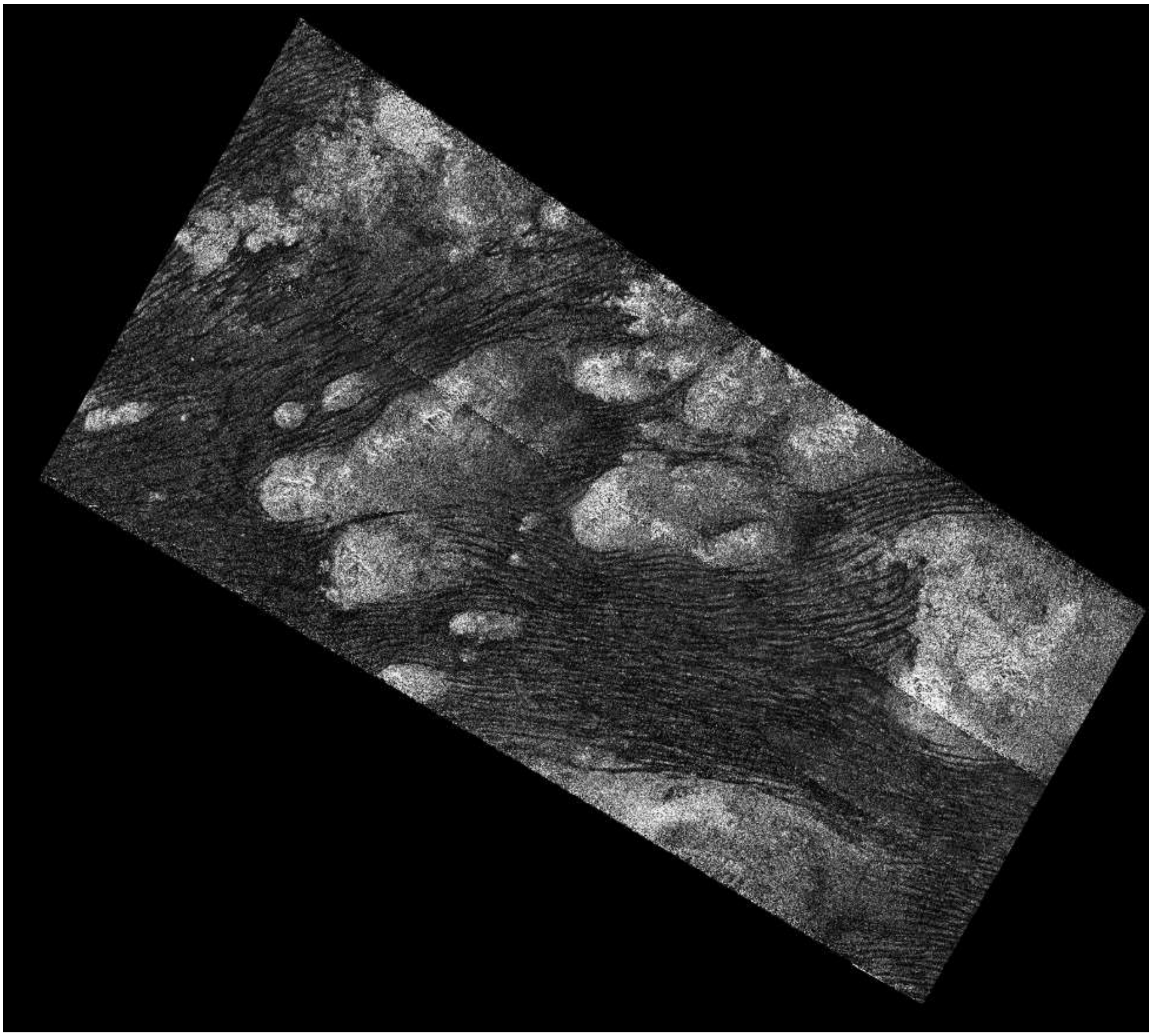

Figure 10.19: **Flowing Dunes of Shangri-La: The Shangri-La Sand Sea on Titan is shown in this image from the Synthetic Aperture radar (SAR) on Cassini. Hundreds of sand dunes are visible as dark lines snaking across the surface. These dunes display patterns of undulation and divergence around elevated mountains (which appear bright to the radar), thereby showing the direction of wind and sand transport on the surface.**

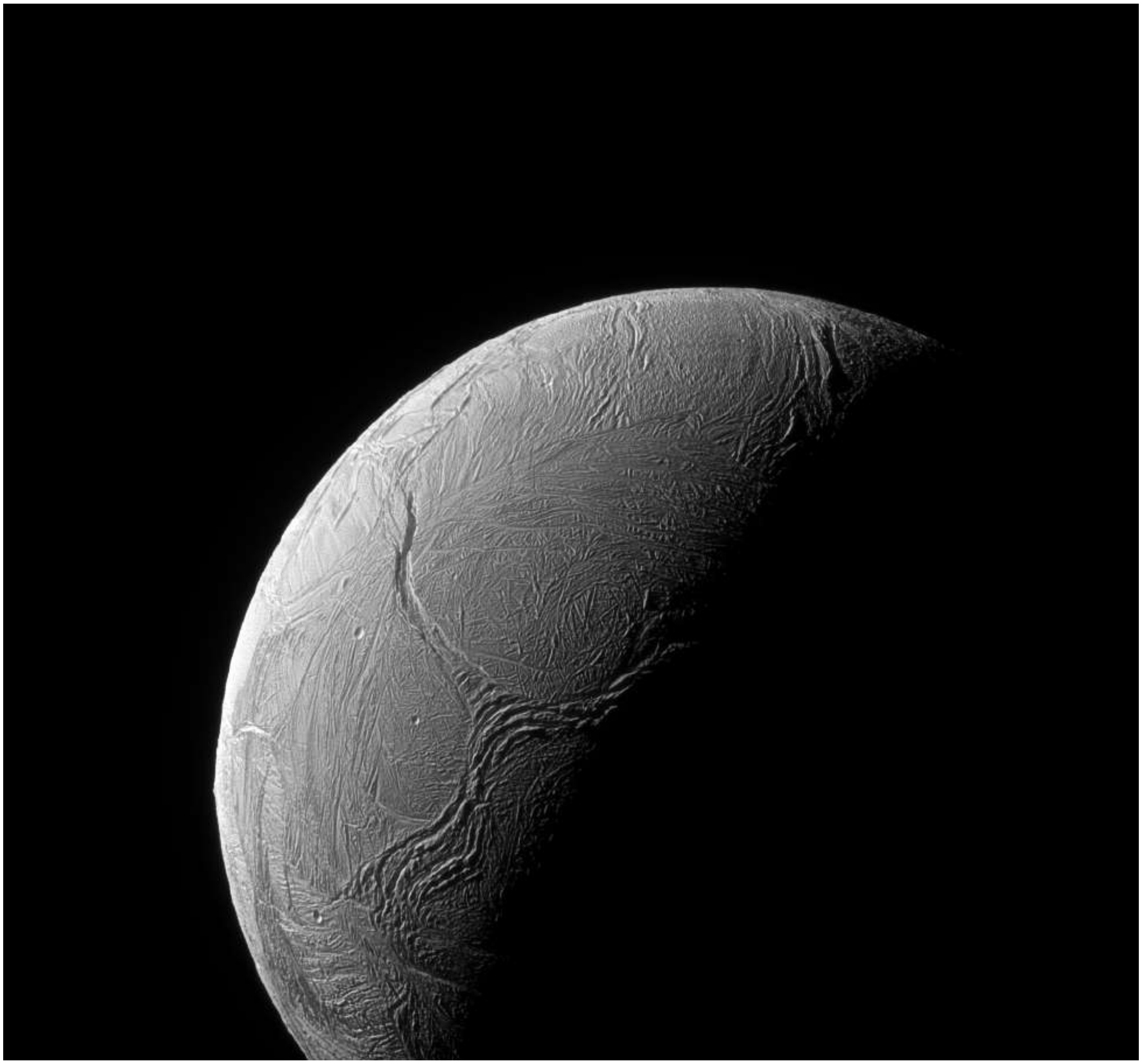

Figure 10.20: **Y Marks the Spot: A sinuous feature snakes northward from Enceladus' south pole like a giant tentacle. This feature, which stretches from the terminator near center, toward upper left, is actually tectonic in nature, created by stresses in Enceladus' icy shell.**

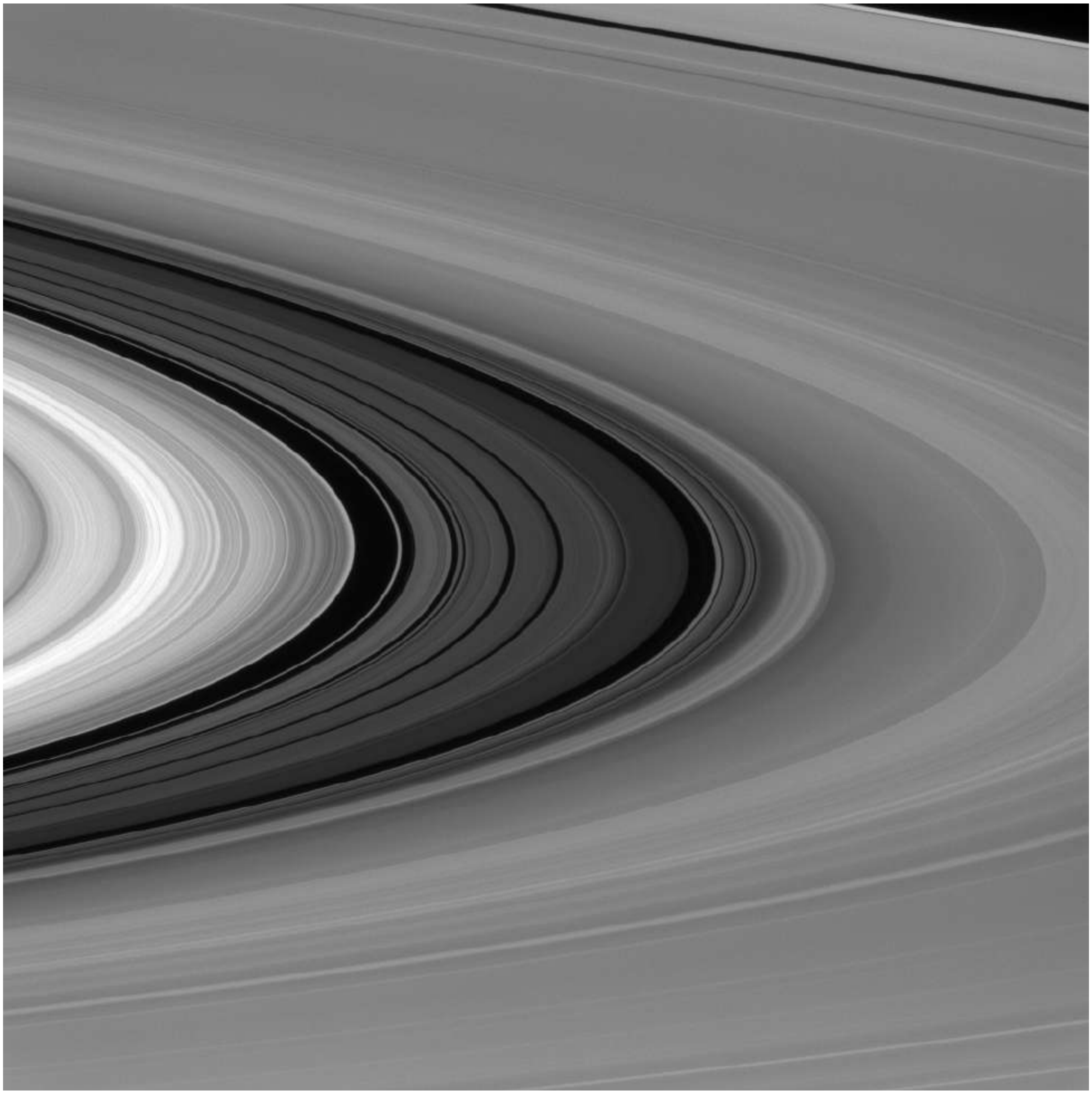

Figure 10.21: **The Great Divide: It's difficult to get a sense of scale when viewing Saturn's rings, but the Cassini Division (seen here between the bright B ring and dimmer A ring) is almost as wide as the planet Mercury. The 2,980-mile-wide (4,800-kilometer-wide) division in Saturn's rings is thought to be caused by the moon Mimas. Particles within the division orbit Saturn almost exactly twice for every time that Mimas orbits, leading to a build-up of gravitational nudges from the moon. These repeated gravitational interactions sculpt the outer edge of the B ring and keep its particles from drifting into the Cassini Division.**

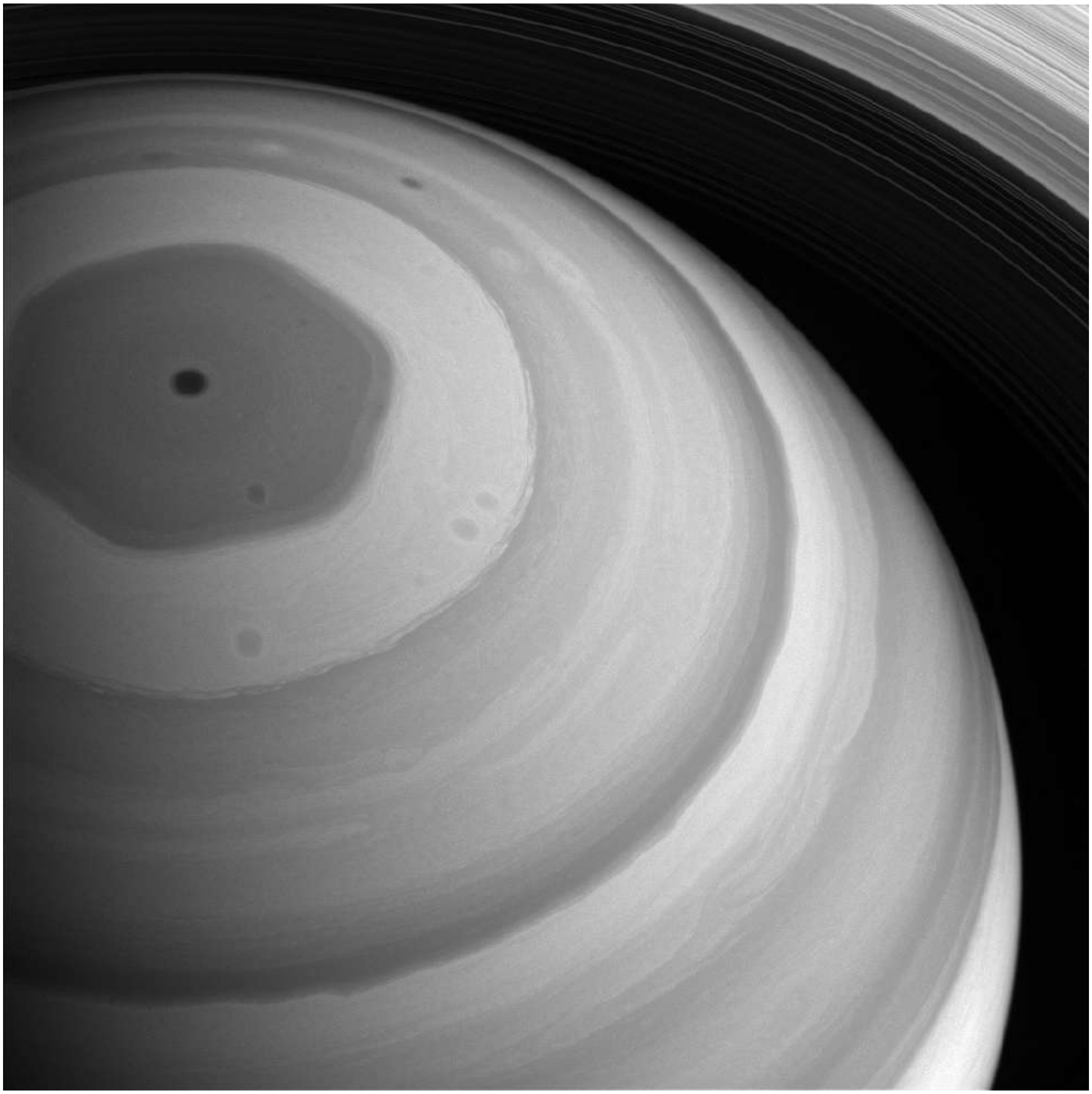

Figure 10.22: **Basking in Light: Sunlight truly has come to Saturn's north pole. The whole northern region is bathed in sunlight in this view from late 2016, feeble though the light may be at Saturn's distant domain in the solar system. The hexagon-shaped jet-stream is fully illuminated here. In this image, the planet appears darker in regions where the cloud deck is lower, such the region interior to the hexagon.**

10.5 Life elsewhere in the universe

Formation of the Sun and the Earth

Our local star, the Sun, was formed from molecular clouds in interstellar space, which had been produced by the explosion of earlier stars. Our Sun contains mainly hydrogen and a little helium, with very small amounts of heavier elements. The vast amounts of energy produced by the sun come mainly from a nuclear reaction in which hydrogen is converted into helium.

There were clouds of containing not only hydrogen and helium, but also heavier elements left swirling around the infant Sun. Gradually, over many millions of years, these condensed through a process of collision and accretion, to form the planets. In the four relatively small inner planets, Mercury, Venus, Earth and Mars, heavy elements predominate, while in the giants, Jupiter, Saturn, Uranus and Neptune, we find lighter elements.

The Sun accounts for 99.86% of the solar system's mass, while the four giant planets contain 99% of the remaining mass.

One *astronomical unit* (1 AU) is, by definition, the average distance of the earth from the sun, i.e. approximately 93 million miles or 150 million kilometers. In terms of this unit, the average distances of the planets from the sun are as follows: Mercury, 0.387 AU; Venus, 0.722 AU; Earth, 1.000 AU; Mars, 1.52 AU; Jupiter, 5.20 AU; Saturn, 9.58 AU; Uranus, 19.2 AU; Neptune, 30.1 AU.

The Solar System also includes the asteroid belt, which lies between the orbits of Mars and Jupiter; the Kuiper belt and scattered disc, which are populations of trans-Neptunian objects; the dwarf planets, Ceres, Pluto and Eris; and the comets. Many of the bodies in the solar system, including six of the planets, have natural satellites or moons. The Earth's moon was produced by collision with a Mars-sized body, soon after the formation of the Earth.

Of the four inner planets, the Earth is the only one that has large amounts of liquid water on its surface. When the Earth cooled sufficiently after the violent collision that gave us our Moon, oceans began to form, and life is believed to have originated in the oceans, approximately 3.8 billion years before the present.

Extremely early life on earth

On December 18, 2017, scientists from the University of California published an article in *Science News* entitled *Ancient fossil microorganisms indicate that life in the universe is common.* According to the article:

"A new analysis of the oldest known fossil microorganisms provides strong evidence to support an increasingly widespread understanding that life in the universe is common.

"The microorganisms, from Western Australia, are 3.465 billion years old. Scientists from UCLA and the University of Wisconsin-Madison report today in the journal Proceedings of the National Academy of Sciences that two of the species they studied appear to

Figure 10.23: **Much experimental evidence supports the Standard Model of cosmology, according to which our Universe began in an enormously hot and dense state 15.72 billion years ago, from which it is exploding outward. By 10 billion years before the present it had cooled enough for the first stars to form. Our own local star, the Sun, was formed 4.54 billion years ago from dust clouds left when earlier stars exploded.**

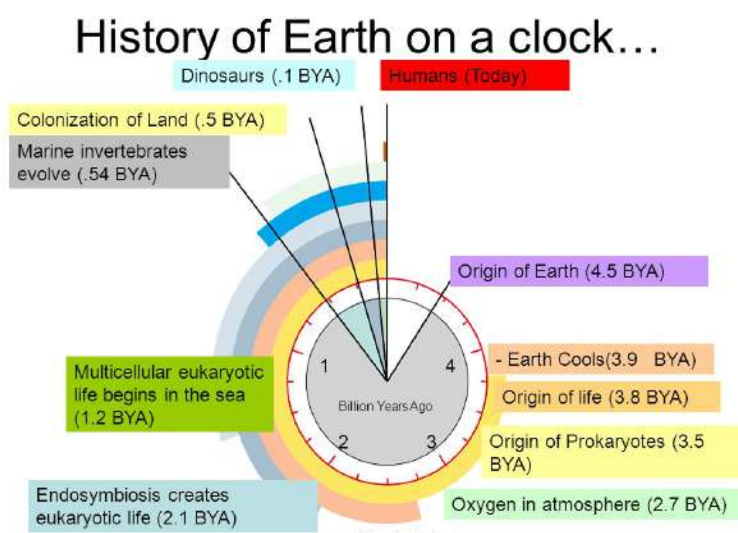

Figure 10.24: **The Earth was formed 4.54 billion years ago. Life on earth originated approximately 3.8 billion years ago (3.8 BYA).**

Figure 10.25: **This figure shows the relative sizes of the planets. Closest to the Sun are the relatively small terrestrial planets, Mercury, Venus, Earth and Mars, composed of metals and rock. Farther out are two gas giants, Jupiter and Saturn, which are composed mainly of hydrogen and helium. Still farther out are two ice giants, Uranus and Neptune, which are composed mainly of frozen water, frozen ammonia and frozen methane. The distances of the planets from the Sun shown in this figure are not realistic. The planetary orbits lie in roughly in the same plane, which is called the ecliptic, and all the planets circle the Sun in the same direction.**

have performed a primitive form of photosynthesis, another apparently produced methane gas, and two others appear to have consumed methane and used it to build their cell walls.

"The evidence that a diverse group of organisms had already evolved extremely early in the Earth's history, combined with scientists' knowledge of the vast number of stars in the universe and the growing understanding that planets orbit so many of them, strengthens the case for life existing elsewhere in the universe because it would be extremely unlikely that life formed quickly on Earth but did not arise anywhere else."

Suggestions for further reading

1. James Gleick, *Moon Fever* [review of Oliver Morton, The Moon: A History of the Future; Apollo's Muse: The Moon in the Age of Photography, an exhibition at the Metropolitan Museum of Art, New York City, 3 July - 22 September 2019
2. Douglas Brinkley, *American Moonshot: John F. Kennedy and the Great Space Race.*
3. Brandon R. Brown, *The Apollo Chronicles: Engineering America's First Moon Missions.*
4. Roger D. Launius, *Reaching for the Moon: A Short History of the Space Race*
5. *Apollo 11*, a documentary film directed by Todd Douglas Miller.
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