# 1

# Astronomy through the centuries

**What we learn in this chapter**

Celestial measurements reaching back 3000 years or more were carried out in many cultures worldwide. **Early astronomers** in Greece deduced important conclusions about the nature of the **earth** and the **solar system**. Modern astronomy began in the **renaissance** with the observations of **Tycho Brahe** and **Galileo** and the theoretical work of **Kepler** and **Newton**. The progress of our knowledge of the sky may be traced through a series of **major discoveries** which often follow the development of new **technologies** such as the **telescope**, **computers**, and **space observatories.** Astronomy is now carried out across the entire electromagnetic spectrum from the **radio** to the **gamma ray** (see cover illustrations) as well as with **cosmic rays**, **neutrinos,** and **gravitational waves**. The mutual dependence of **theory** and **observation** has led to major advances in the understanding of a wide diversity of celestial objects such as **stars**, **supernova remnants**, **galaxies,** and the **universe** itself. Current observations reveal important phenomena that are not understood. The promise of **new fundamental discoveries** remains high.

## 1.1 Introduction

This introductory chapter provides a brief sketch of the history of astronomy with emphasis upon some pivotal ideas and discoveries. The ideas presented here are covered more systematically in subsequent chapters of this or subsequent planned volumes.

## 1.2 Early development of astronomy

### *First astronomers*

The rhythmic motions of the stars, the planets, and the sun in the sky have fascinated humankind from the earliest of times. The motions were given religious significance

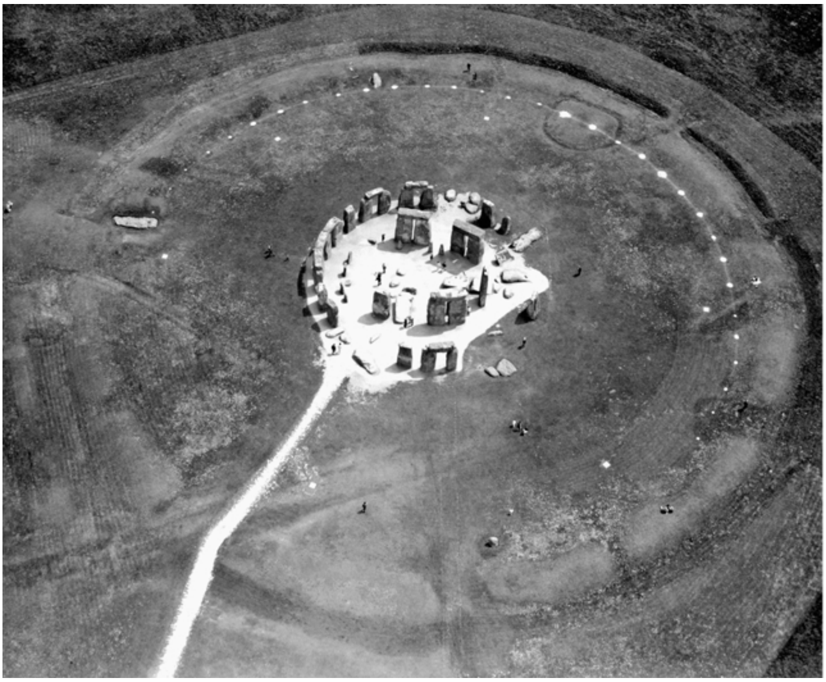

Figure 1.1. Stonehenge, an early astronomical observatory used for tracking the sun and moon in their seasonal excursions. [© Crown copyright, NMR]

and were useful agricultural indicators. The sun's motion from south to north and back again marked the times of planting and harvesting. The annual motion of the sun against the background of the much more distant stars could also be followed and recorded, as could the motions of the moon and planets. This made possible predictions of the future motions of the sun and moon. Successful forecasters of the dramatic eclipses of the sun seemed to be in touch with the deities.

The periodic motions of the sun and moon were noted and described with calendars as early as the thirteenth century BCE in China. Surviving physical structures appear to be related to the motions of celestial bodies. Notable are an eighth century BCE sundial in Egypt and the assemblage of large stones at Stonehenge in England dating from about 2000 BCE (Fig. 1)[1]. The Babylonians and Assyrians in the Middle East are known to have been active astronomers in the several centuries BCE (The designations BCE "before common era" and CE "common era" are equivalent to BC and AD respectively.)

[1] In an attempt to minimize redundant numbers in the text, we omit the chapter designation in references to figures within the chapter in which the figure occurs, e.g. "Fig. 2". For references to figures in another chapter, say, Chapter 3, the reference is the conventional format "Fig. 3.2". Problem, equation, and section references are treated similarly. Equations are usually referenced in the text as a number within parentheses without the prefix "Eq.", for example: "as shown in (10)" for equations within the chapter, or "given in (5.10)" for Eq. 10 of Chapter 5.

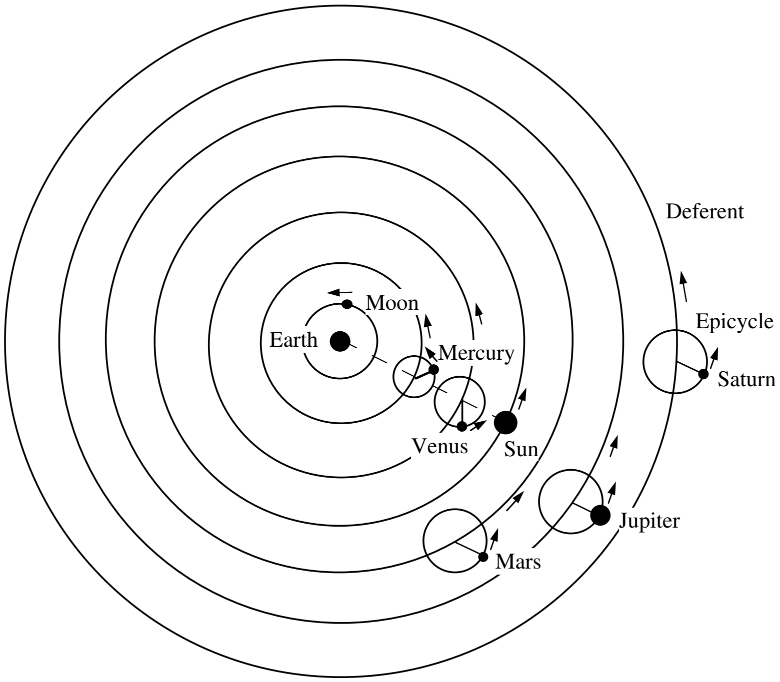


Figure 1.2. Ptolemaic system, not drawn to scale. The earth is at the center, the moon and sun follow circular paths and the planets follow (small) circular orbits (epicycles) the centers of which move regularly along large circular orbits known as deferents. Elliptical orbits are taken into account by offsetting slightly the centers of the deferents and also the earth itself from a geometrical "center".

Astronomy flourished under Greek culture (∼600 BCE to ∼400 CE) with important contributions by Aristotle, Aristarchus of Samos, Hipparchus, Ptolemy, and others. The Greek astronomers deduced important characteristics of the solar system. For example, Aristotle (384–322 BCE) argued from observations that the earth is spherical, and Aristarchus (310–230 BCE) made measurements to obtain the sizes and distances of the sun and moon relative to the size of the earth. Ptolemy (∼140 CE) developed a complicated earth-centered model (Fig. 2) for the solar system which predicted fairly well the complicated motions of the planets as viewed from the earth.

The advance of astronomy in Europe faltered during the following 13 centuries. Nevertheless the sky continued to be observed in many cultures, e.g., the Hindu, Arabian, and Oriental. The sudden appearances of bright new and temporary "guest" stars in the sky were noted by the Chinese, Japanese, Koreans, Arabs, and Europeans. The most famous of all such objects, the Crab supernova, was recorded in 1054 by Chinese and Japanese astronomers. It is now a beautiful diffuse nebula in the sky (Fig. 3). The Mayan culture of Central America independently developed

(a)

(b)

Figure 1.3. Crab nebula, the remnant of a supernova explosion observed in 1054 CE. The neutron-star pulsar is indicated (arrow). The filters used for the two photos stress (a) the blue diffuse synchrotron radiation and the pulsar and (b) the strong filamentary structure that glows red from hydrogen transitions. The scales of the two photos are slightly different. The Crab is about 4′ in extent and ~6000 LY distant. The orientation is north up and east to the left – as if you were looking at the sky while lying on your back with your head to the north; this is the standard astronomical convention. [(a) Jay Gallagher (U. Wisconsin)/WIYN/NOAO/NSF.; (b) FORS Team, VLT, ESO]

strong astronomical traditions, including the creation of a sophisticated calendar that could be used, for example, to predict the positions of Venus.

### *Renaissance*

The Renaissance period in Europe brought about great advances in many intellectual fields including astronomy. The Polish monk Nicholaus Copernicus (1473–1543) proposed the solar-centered model of the planetary system. The Dane Tycho Brahe (1546–1601, Fig. 4) used elegant mechanical devices to measure planetary positions to a precision of $\sim 1'$ (1 arcminute)[1] and, over many years, recorded the daily positions of the sun, moon, and planets.

The German Johannes Kepler (1571–1630, Fig. 4), Brahe's assistant for a time, had substantial mathematical skills and attempted to find a mathematical model that would match Brahe's data. After much effort, he found that the apparent motions of Mars in the sky could be described simply if Mars' orbit about the sun is taken to be an ellipse. He summarized his work with the three laws now known as Kepler's laws of planetary motion. They are: (*i*) each planet moves along an elliptical path with the sun at one focus of the ellipse, (*ii*) the line joining the sun and a planet sweeps out equal areas in equal intervals of time, and (*iii*) the squares of the periods $P$ (of rotation about the sun) of the several planets are proportional to the cubes of the semimajor axes $a$ of their respective elliptical tracks,

$$P^2 \propto a^3 \qquad \text{(Kepler's third law)} \qquad (1.1)$$

This formulation laid the foundation for the gravitational interpretation of the motions by Newton in the next century.

Galileo Galilei (1564–1642, Fig. 4), a contemporary of Kepler and an Italian, carried out mechanical experiments and articulated the *law of inertia* which holds that the state of constant motion is as natural as that of a body at rest. He adopted the Copernican theory of the planets, and ran afoul of the church authorities who declared the theory to be "false and absurd". His book, *Dialog on the Two Great World Systems* published in 1632, played a significant role in the acceptance of the Copernican view of the solar system. Galileo was the first to make extensive use of the *telescope*, beginning in 1609.

The telescope was an epic technical advance in astronomy because, in effect, it enlarged the eye; it could collect all the light impinging on the objective lens and direct it into the observer's eye. Since the objective lens was much larger than the lens of the eye, more light could be collected in a given time and fainter objects could be seen. The associated magnification allowed fine details to be resolved. Galileo was the first to detect the satellites (moons) of Jupiter and to determine

[1] The measures of angle are degree (°), arcmin (′), and arcsec (″) where $60'' = 1'$ and $60' = 1°$.


Figure 1.4. The three astronomers who pioneered modern astronomy. [(a) Tycho Brahe's Glada Vänner; (b) portrait by Justus Sustermans; (c) Johannes Kepler Gesammelte Werke, C. H. Beck, 1937. All are on internet: "Astronomy Picture of the Day", NASA/GSFC and Michigan Tech U.]

their orbital periods. He showed that the heavens were not perfect and immutable; the earth's moon was found to have a very irregular surface and the sun was found to have dark "imperfections", now known as *sunspots*.

The Englishman Isaac Newton (1643–1727; Gregorian calendar) was born 13 years after the death of Kepler and almost exactly one year after Galileo died.

His study of mechanics led to three laws, *Newton's laws*, which are stated here in contemporary terms: (*i*) the vector momentum $\boldsymbol{p} = m\boldsymbol{v}$ of a body of mass $m$ moving with velocity $\boldsymbol{v}$ is conserved in the absence of an applied force[1] (this is a restatement of Galileo's law of inertia), (*ii*) a force applied to a body brings about a change of momentum,

$$\boldsymbol{F} = \frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} \qquad \text{(Newton's second law)} \qquad (1.2)$$

and (*iii*) the force $\boldsymbol{F}_{1,2}$ on one body due to second body is matched by an opposing force of equal magnitude $\boldsymbol{F}_{2,1}$ on the second body due to the first,

$$\boldsymbol{F}_{1,2} = -\boldsymbol{F}_{2,1} \qquad \text{(Newton's third law)} \qquad (1.3)$$

These laws are the bases of *Newtonian mechanics* which remains the essence of much modern mechanical theory and practice. It fails when the speeds of the bodies approach the speed of light and on atomic scales.

Newton was able to show that a *gravitational force* of a particular kind described perfectly the planetary motions described by Kepler. This force is an attractive gravitational force $\boldsymbol{F}$ between two bodies that depends proportionally upon the masses ($m_1$, $m_2$) and inversely with the squared distance $r^2$ between them,

$$\boldsymbol{F} \propto -\frac{m_1 m_2}{r^2}\hat{\boldsymbol{r}} \qquad \text{(Newton's law of gravitation)} \qquad (1.4)$$

where $\hat{\mathbf{r}}$ is the unit vector along the line connecting the two bodies. Such a force leads directly to the elliptical orbits, to the speeds of motion in the planetary orbit, and to the variation of period with semimajor axis described by Kepler's three laws. Thus, all the celestial motions of the earth, moon, and sun could be explained with a single underlying force. This understanding of the role of gravity together with the invention of the telescope set astronomy solidly on a path of quantitative measurements and physical interpretation, i.e., *astrophysics*.

## 1.3 Technology revolution

### *Telescopes, photography, electronics, and computers*

The study of the sky continued with the development of larger and larger telescopes. Generally these were refractive instruments wherein the light passes through the lenses, as in a pair of binoculars. The glass refracts the different colors of light slightly differently (*chromatic aberration*) so that perfect focusing is difficult to attain. This led to reflecting telescopes that make use of curved mirrors. In this case, all wavelengths impinging at a position of the mirror from a given angle are

[1] We use italic boldface characters to signify vector quantities and the hat symbol to indicate unit vectors.

reflected in the same direction. The 5-m diameter mirror of the large telescope on Palomar Mountain in California (long known as the "200 inch") was completed in 1949. It was the world's largest telescope for many years. In the 1960s and 1970s, several 4-m diameter telescopes were built as was a 6-m instrument in the Soviet Union. At this writing, the two Keck 10-m telescopes in Hawaii are the largest, but other large telescopes are not far behind. New technologies which allow telescopes to compensate for the blurring of starlight by the earth's atmosphere are now coming on line.

Photography was an epochal development for astronomy in the nineteenth century. Before this, the faintest object detectable was limited by the number of *photons* (the quanta of light) that could be collected in the integration time of the eye, ∼30 ms (millisecond) to ∼250 ms if dark adapted. If a piece of film is placed at the focus of a telescope, the photons can be collected for periods up to and exceeding 1 hour. This allowed the detection of objects many orders of magnitude fainter than could be seen by eye. A photograph could record not only an image of the sky, but also the *spectrum* of a celestial object. The latter shows the distribution of energy as a function of wavelength or frequency. The light from the object is dispersed into its constituent colors with a prism or grating before being imaged onto the film. Large telescopes together with photography and spectroscopy greatly enlarge the domains of quantitative measurements available to astronomers.

Since the mid-twentieth century, more sensitive electronic detection devices have come into use. Examples are the *photomultiplier tube*, the *image intensifier*, and more recently, the *charge-coupled detector* (CCD). Computers have come into wide use for the control of the telescope pointing and for analysis of the data during and after the observation. The greatly increased efficiencies of data collection and of analysis capability go hand in hand in increasing the effectiveness of the astronomer and his or her ability to study fainter and more distant objects, to obtain spectra of many objects simultaneously, or to measure bright sources with extremely high time resolution. In the latter case, changes of x-ray intensity on sub-millisecond time scales probe the swirling of ionized matter around neutron stars and black holes.

### *Non-optical astronomy*

Electromagnetic radiation at radio frequencies was discovered by Heinrich Hertz in 1888. This eventually led to the discovery of radio emission from the sky by Carl Jansky in 1931. This opened up the field of *radio astronomy*, an entirely new domain of astronomy that has turned out to be as rich as conventional optical astronomy. Entirely new phenomena have been discovered and studied. Examples are the distant *quasars* (described below) and the neutral hydrogen gas that permeates interstellar space. The invention of the maser and the use of supercooled detectors have greatly increased the sensitivity and frequency resolution of radio telescopes. Multiple radio telescopes spread over large distances (1 km to 5 000 km or more) are now used in concert to mimic a single large telescope with angular resolutions down to better than 0.001″ (arcseconds).

The Very Large Array (VLA) of 27 large radio telescopes extending over about 40 km of New Mexico desert operates on this principle. With its large area it has excellent sensitivity. It has produced many beautiful images of radio objects in the sky with angular resolution comparable to that of ground-based optical astronomy (∼1″).

The atmosphere of the earth is a great impediment to many kinds of astronomy. Photons over large bands of frequencies can not penetrate it. The advent of space vehicles from which observations could be made opened up the field of *x-ray astronomy*. Like radio astronomy, this field led to the discovery of a variety of new phenomena, such as neutron stars in orbit with ordinary nuclear-burning stars, high-temperature shock waves in supernova remnants, black holes (described below), and high-energy phenomena in distant quasars.

Space vehicles have also made possible the study of the *ultraviolet radiation* from nearby stars and distant galaxies and *gamma-ray emission* from pulsars and from the nuclei of active galaxies. *Infrared astronomy* can be carried out at only a few frequencies from the ground, but in space a wide band of frequencies are accessible. Infrared astronomers can peer into dust and gas clouds to detect newly formed stars. Space vehicles also carry optical/ultraviolet telescopes above the atmosphere to provide very high angular resolutions, $\lesssim$0.05″ compared to the ∼1″ normally attained below the atmosphere. This is a major feature of the Hubble Space Telescope.

The space program also has provided a platform for *in situ* observations of the planets and their satellites (moons); the spacecraft carries instruments to the near vicinity of the planet. These missions carry out a diversity of studies in a number of wavebands (radio through the ultraviolet) as well as magnetic, cosmic-ray, and plasma studies. The Voyager missions visited Jupiter, Saturn, Uranus and Neptune. One of them will soon leave the solar-system *heliosphere* and thus be able to carry out direct measurements of the *interstellar medium*.

A given celestial object can often be studied in several of the frequency domains from the radio to gamma rays. Each provides complementary information about the object. For example, the x rays provide information about very hot regions (∼10 million kelvin) while infrared radiation reflects temperatures of a few thousand degrees or less. The use of all this information together is a powerful way to determine the underlying nature of a class of celestial objects. This type of research has come to be known as *multi-frequency astronomy*. Sky maps at various frequencies (cover illustrations) illustrate the variation of the character of the sky with frequency.

Signals other than the electromagnetic waves also provide information about the cosmos. Direct studies of *cosmic rays* (energetic protons, helium nuclei, etc.) circulating in the vast spaces between the stars are carried out at sea level and also from space. These high-energy particles were probably accelerated to such energies, at least in part, by the shock waves of supernova explosions.

*Neutrinos*, neutral quanta that interact very weakly with other matter, have been detected from the nuclear reactions in the center of the sun and from the spectacular implosion of a star in the Large Magellanic Cloud, an easily visible stellar system in the southern sky. The outburst is known as *supernova 1987A*. Neutrino detectors are placed underground to minimize background.

The detection of gravitational waves predicted by the theory of general relativity is still a challenge. Observatories to search for them with high sensitivity are now beginning operations, such as the US Laser Interferometer Gravitational-wave Observatory (LIGO) with interferometer "antennas" in Washington State and Louisiana or the German–UK GEO-600. A likely candidate source of gravitational waves is a binary system of two neutron stars in the last stages of spiraling into each other to form a black hole.

## 1.4 Interplay of observation and theory

The objective of astronomical studies is to learn about the nature of the celestial objects, including their sizes, masses, constituents, and the basic physical processes that take place within or near them. Progress is made through an interplay of observational data and theoretical insight. Observations guide the theorist and theories suggest observations. The pace of this interplay greatly accelerated in the late nineteenth and twentieth centuries due to the rapid increase in technical capability described above. The recent history of astronomy is replete with examples of this symbiosis of observation and theory.

### *Stars and nebulae*

Dark absorption lines were discovered in the solar spectrum in 1802, and Joseph Fraunhofer (1787–1826) recorded the locations of about 600 of them. Comparison to spectra emitted by gases and solids in earth laboratories showed that the gaseous outer layer of the sun contains elements well known on earth. The quantum theory developed in the 1920s yields the frequencies of radiation emitted by atoms as well as the probabilities of emission under various conditions of density