

Chapter 2

Historical Background

It is a common perception that astronomy is one of the oldest occupations in the history of mankind. While this is probably true, ancient views contain very little about the origins of stars. Their everlasting presence in the night sky made stars widely used benchmarks for navigation. Though it always was and still is a spectacular event once a new light, a nova, a new star appears in the sky. Such new lights are either illuminated moving bodies within our Solar System, or a supernova and thus the death of a star, or some other phases in the late evolution of stars. Never is a normal star really born in these cases. The birth of a star always happens in the darkness of cosmic dust and is therefore not visible to human eyes (see Figure 2.1). In fact, when a newborn star finally becomes visible, it is already at the stage of kindergarten in terms of human growth. It takes the most modern of observational techniques and the entire accessible bandwidth of the electromagnetic spectrum to peek into the hatcheries of stars.

2.1 And There Was Light?

A historical introduction to stellar formation is strictly limited to the most recent time periods. Modern science does not recognize too many beliefs from ancient periods as facts. For example, timescales are specifically important for the physical mechanisms of the formation and early evolution of stars. Biblical records leave no doubt that the world was created by God in six days and the formation of the Sun and stars was a hard day's job. Allegorically speaking there is nothing wrong with that unless the attempt is made to match these biblical timescales with physically observed time spans. Then timescales from thousands to millions of years are relevant, whereas days and weeks hardly appear in this context. Today it is known that it takes about 100,000 years for a molecular cloud to collapse and more than many million years for most stars to contract enough to start hydrogen fusion, not to speak of creating solar systems and planets. One also realizes that planets take even longer to become habitable. In the case of the Earth it took billions of years.

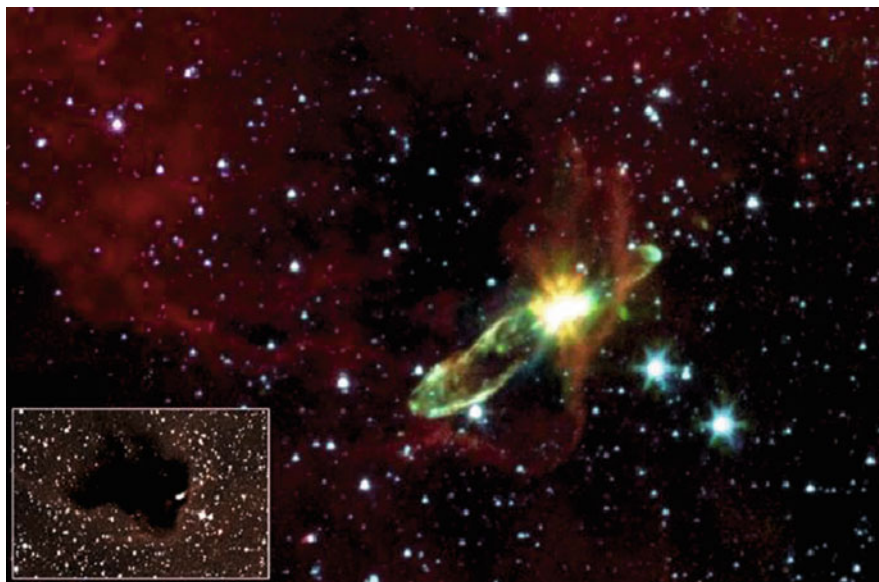


Fig. 2.1 This breathtaking image shows a newborn proto-Sun associated with the Herbig–Haro outflow object *HH 46* (see the bright loop-like strings pointing away from the star). The inset in the lower left corner shows the optical image of the same region. The proto-Sun with its outflow is hidden in a dense cloud. Credit: NASA/JPL/Caltec/A.Noriega-Crespo(SSC/Caltech)

The following few sections are an attempt to briefly summarize the road from ancient views to the point when the understanding of physical processes in connection with observations of stellar properties reached a level that permitted the first physical treatment of stellar formation and evolution. Though the presented material also introduces the reader to some basic facts of modern physics and astronomy, the emphasis of this chapter is not a substitute for introductory textbooks on physics and astronomy. The chapter resembles more an investigation of the developments and scientific milestones that led to the pursuit of modern star formation studies.

2.1.1 From Ptolemy to Newton

It took humankind until the dawn of the New Age to put basic pieces together and to accept proof over belief and superstition. The geocentric concept of Claudius Ptolemaeus, or Ptolemy, dominated the views of the world from ancient times to the 16th century. He walked the Earth approximately between the years 175 and 100 BC and, although he lived in the Egyptian city Alexandria, he was more a scientist of hellenistic origin and many of his views are based on the cosmological concepts of Aristotle (384 BC), a student of Plato. In his work ‘Hypotheses of the

Planets' Ptolemy describes a system of the worlds where Earth as a sphere reigns at the very center of a concentric system of eight spheres containing the Moon, Mercury, Venus, the Sun, Mars, Jupiter, and Saturn. The eighth and last sphere belonged to the stars. They all had the same distance from earth and were fixed to the sphere. Constellations, as well as their size, consistency and color were eternal. The question about the structure of planets and stars was not pursued and the mystic element called 'ether' was introduced instead to fill the space within and between celestial entities – a concept that lasted until the 20th century. Sometimes stars were also referred to as 'crystalline'. For over 1,500 years Ptolemy's work was the main astronomical resource in Europe and the Orient.

After the medieval period, Earth resided uncontested at the center of the universe and the stars were still either lights fixed to the celestial sphere or little holes in a sphere surrounded by heaven's fire. How much the Ptolemaic scheme was imprinted into the most fundamental beliefs is shown in a picture from a bible print in the 16th century depicting the traditional Judeo-Christian view of the *Genesis*, the Bible's version of the creation in which God makes the Earth and the Cosmos in six days (see Fig. 2.2). Even after Nicolaus Copernicus published his famous book series *De Revolutionibus orbium coelestium libri sex* in 1543, which featured today's heliocentric system, Ptolemy's model prevailed for quite some time. The first indication that something could be missing in the Ptolemaic system came with the observation of a supernova in the constellation Cassiopeia by Tycho Brahe in 1572. Following Brahe's legacy it was at last Johannes Kepler with his publication *De Harmonice Mundi* in 1619 and Galileo Galilei's 'Il Saggiatore' from 1623 that not only placed the Sun as the center of the solar system but also established observations as a powerful means to oppose the clerical dogma.

This was not only a triumph of science, it had specific relevance from the standpoint of stellar evolution as it was realized that the Sun and the planets are one system. When Isaac Newton published his *Naturalis philosophiae principia mathematica* in 1687 the formal groundwork of celestial mechanics was laid.

2.1.2 Stars Far – Parallax

A remaining issue with Ptolemy's picture which posed quite a severe problem for the Copernican system was the fact that Ptolemy postulated stationary stars pinned to the celestial sphere at equal distance. If, however, Earth moves around the Sun one should be able to observe an apparent motion in the star's positions on the sky.

The only way out of the problem was to postulate that stars are so far away that the expected yearly displacement is too small to measure. In fact, the angle between two observations at two fixed positions should give the distance to the stars. Such an angle is called *parallax*. For quite a long time it seemed that Ptolemy's postulate would prevail as all attempts to find this angle were unsuccessful. It was a rocky road from E. Halley's discovery in 1718 that stars do have proper motions to the first successful measurement of the parallax of 61 Cygni by F. W. Bessel at



Fig. 2.2 Genesis view from Martin Luther's *Biblia*, published by Hans Lufft at Wittenberg in 1534. The impression (by Lucas Cranach) shows the Earth at the center and the Sun and stars in the waters of the firmament positioned at the inner edge of an outer sphere. Credit: from *Gestaltung religiöser Kunst im Unterricht*, Leipzig, Germany

a distance of 11.1 light years. The angle measured was only a fraction of an arc second ($0.31''$) and represented the first high-precision parallax measurement. Most recently the astrometry satellite *Hipparcos*, launched in 1989, determined parallaxes

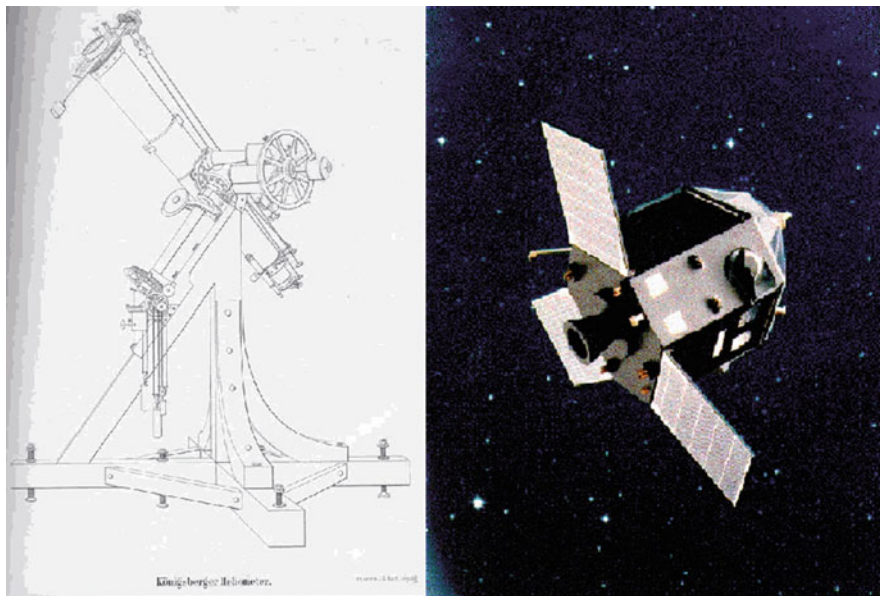


Fig. 2.3 (left) The Königsberger Heliometer Bessel installed in 1829 to perform parallax measurements with a resolution of 0.05 arc seconds. Credit: The Dudley Observatory, Drawing from the 1830s, Lith. Anst. v. J.G. Bach, Leipzig [5]. (right) An artist's impression of the astrometry satellite *Hipparcos* launched by ESA in 1989. The satellite allowed parallax measurements with 0.00097 arc seconds resolution. Credit: ESA/ESOC

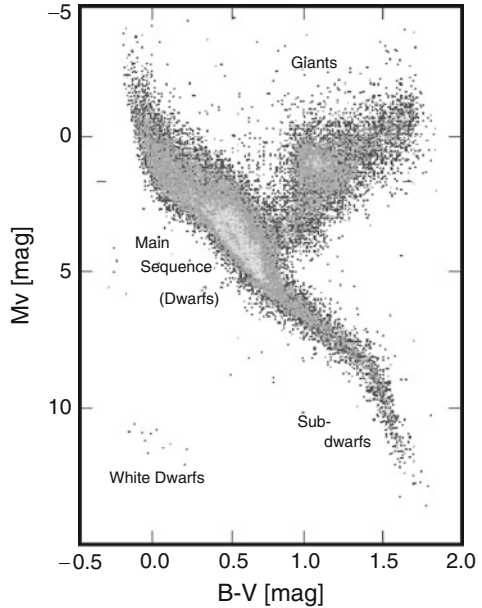
of over 120,000 stars with a precision of 0.001 arc seconds. Data from satellites like *Hipparcos* are essential for today's astronomical research (see Fig. 2.3).

2.1.3 Stars Bright – Photometry

All astronomy preceding the 20th century was related to the perception of the human eye. The 19th century marked a strong rise in the field of stellar photometry. About a hundred years before first attempts were made to define a scale for the brightness of stars, P. Bouguer published some of the earliest photometric measurements in 1729. He believed that the human eye was quite a good indicator of whether two objects have the same brightness and tested this by comparing the apparent brightness of the Moon to that of a standard candle flame. A more quantitative definition was introduced by N. Pogson in 1850. He defined a brightness logarithm on the basis of a decrease in brightness S by the relation

$$\frac{S_1}{S_2} = 10^{0.4(m_1 - m_2)} \quad (2.1)$$

Fig. 2.4 Color-magnitude diagram for 41,704 single stars from the Hipparcos Catalogue with a color error of $\sigma_{B-V} \leq 0.05$ mag. The grayscale indicates the number of stars in a cell of 0.01 mag in color index $B - V$ and 0.05 mag in absolute magnitude M_V . The magnitude was limited to < -5 in the sample. Data from: ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200



for each step $\Delta m = m_1 - m_2$, which he called ‘magnitudo’. One of the greatest astronomical achievements in the 19th century was the publication of various photometric catalogs by F. Argelander, E. Schönfeld and E. C. Pickering containing a total of over 500,000 stars.

It was K. Schwarzschild [1] who opened the door into the 20th century with the creation of the first photographic catalog containing color indices, i.e., photographic minus visual brightness, of unprecedented quality. The key element was the recognition that the color index is a good indicator of the color and thus the temperature of a star. The use of photoelectric devices to perform photometry was first pursued in the early 20th century [2, 16, 17]. The UBV-band system developed in 1951 [18] determines magnitudes in three color bands, the ultraviolet band (U , $\sim 3,500$ Å), the blue band (B , $\sim 4,000$ Å), and the visual band (V , $\sim 5,500$ Å). Today photomultipliers are used to determine magnitudes with an accuracy of less than 0.01 mag and effective temperature measurements of stars to better than 1 percent [19]. Figure 2.4 shows a color-magnitude diagram of over 40,000 stars from data obtained by *Hipparcos*.

2.1.4 Star Light – Spectroscopy

The 19th century also marked, parallel to the development in photometry, the beginning of stellar spectroscopy. Newton had already studied the refraction of light using optical prisms and found out that white sunlight can be dispersed

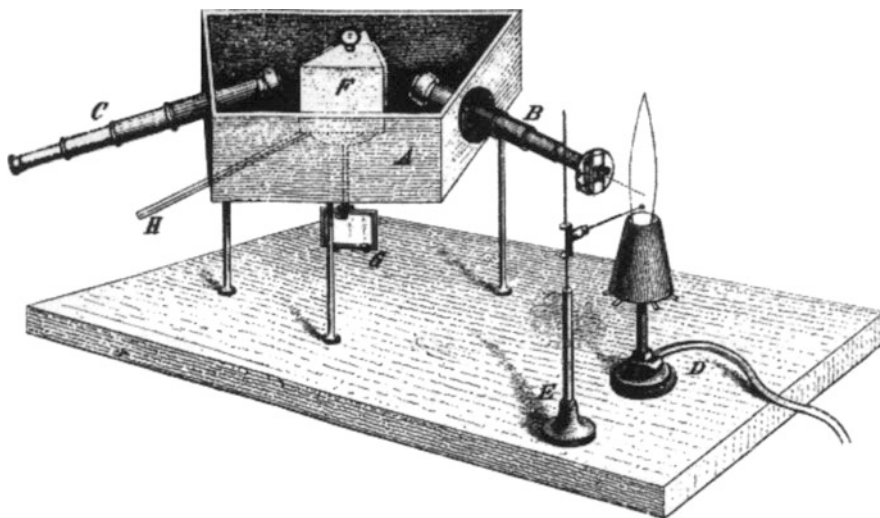


Fig. 2.5 Kirchhoff's and Bunsen's apparatus used for the observation of spectra. The gas flame was incinerated with different chemical elements. A rotating crystal (*F*) at the center diffracted the light from the flame, the diffracted light was then observed with a telescope (*C*). Credit: Kirchhoff and Bunsen [20]

into its colors from blue to red. However it was J. Fraunhofer in 1814 whose detection of dark lines in the spectrum of the Sun and similar lines in stars in 1823, represented a first step towards astrophysics. Not only was it remarkable that the Sun and stars showed similar spectra, but also that the strong lines in the solar spectrum indicated a chemical relation. After publishing the *Chemische Analyse durch Spektralbeobachtungen* in 1860, G. Kirchhoff and R. Bunsen established spectral analysis as an astrophysical tool (see Fig. 2.5).

This discovery sparked a range of activities which ultimately led to an understanding of radiative laws and the classification of stellar spectra against the one from the Sun. What was needed were laboratory measurements to identify elements with observed wavelengths, stellar spectra, and magnitudes and a theory of radiation. When pursuing his spectral analysis in the 1860s Kirchhoff realized that there must be a relation between the absorption and the emission of light. He also noted that various colors in the spectral band correspond to different temperatures – the basis of modern UVB photometry. This led him to the formulation of what is known today as Kirchhoff's law (see Appendix C) which now is one of the most fundamental laws in radiative theory. Kirchhoff assumed 'Hohlraum Strahlung', radiation from a hollow body in thermodynamical equilibrium, which had a spectral shape of what is today simply referred to as a blackbody spectrum (see Fig. A.2).

Vigorous studies were pursued at the Harvard Observatory under E. C. Pickering and A. J. Cannon at the turn of the century and ultimately led to the *Henry Draper Catalogue* released between 1918 and 1924 which contained over 225,000

spectra [21]. This study led to the Harvard (O-B-A-F-G-K-M) classification (or Draper classification) used today. At the time there were some speculations that this classification sequence reflects an evolutionary sequence, though the aspect that stars could evolve had not been exploited yet (see below). E. Hertzsprung and H. N. Russell realized that these classes not only form a sequence, but also correlate with absolute stellar magnitude. This correlation is the very definition of the *Hertzsprung-Russell (HR) Diagram*, one of the most powerful tools in modern astronomy. It not only combines photometry with spectroscopy, but also empirically allows us to make predictions of the size of stars. The Harvard classification shows that stars vary by orders of magnitude in their basic properties like mass, radius and luminosity. The Sun, for example, with a temperature of 5,700 K is then classified

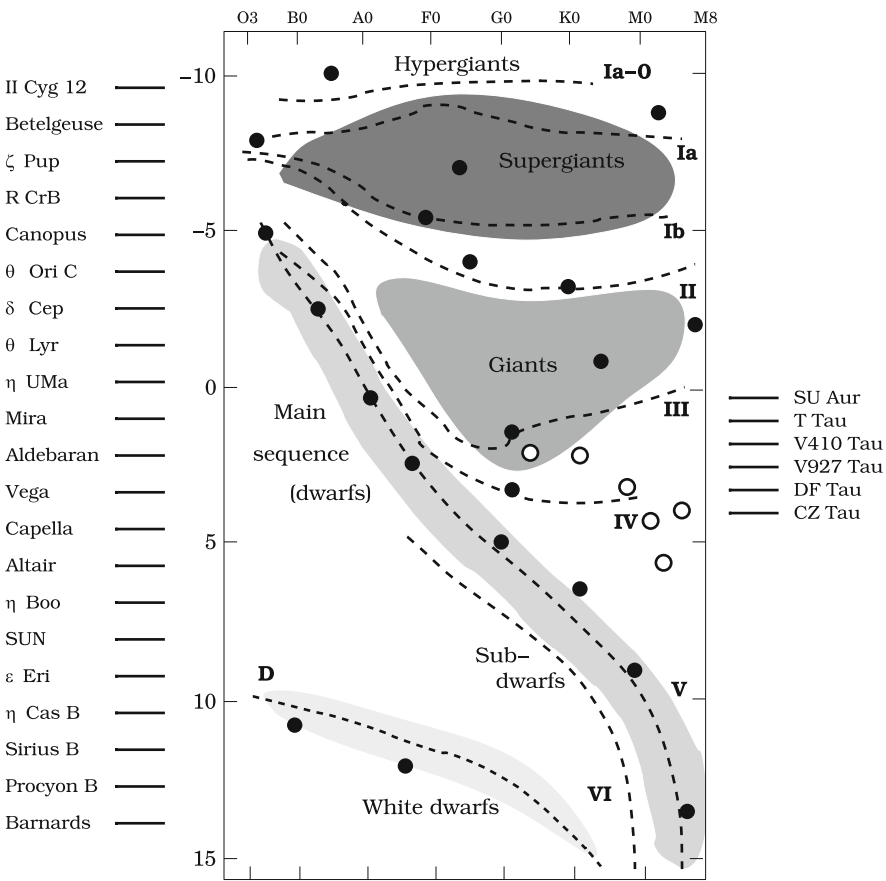


Fig. 2.6 Schematic HR-diagram plotting visual magnitude M_V and spectral classes from the Harvard classification. The plot identifies the various stellar sequences as well as luminosity classes from the MK classification. The filled circles are various examples of stars, which are identified on the left side. The open circles mark young T Tauri stars and are identified on the right side

as a G2 star on the *main sequence*. It was quite obvious that stellar properties require more criteria in order to account for their position in the HR-diagram. One of them is detailed line properties in optical spectra, such as the hydrogen Balmer lines. In 1943, W. W. Morgan and P. C. Keenan at the Yerkes Observatory [22] also introduced luminosity classes 0 to VI, which feature sequences from *class Ia-0 hypergiants* to *class VI subdwarfs* (see Fig. 2.6). The main sequence in this classification is populated by *class V dwarf stars* and represents the beginning of the evolution of fully mature stars once their energy source is entirely controlled by nuclear fusion. In evolutionary terms, young stars are then called *pre-main sequence stars* recognizing that they have not reached the main sequence. The term pre-main sequence has been introduced since the first calculations of evolutionary tracks in the HR-diagram in the mid-1950s.

2.2 The Quest to Understand the Formation of Stars

The historic reflections presented so far have had very little to do with stellar formation but more with general aspects relevant to the history of stellar astronomy. Still, they are important ingredients for putting the following sections into a proper perspective.

2.2.1 The Rise of Star Formation Theory

The first comprehensive account of the formation of the Solar System was formulated by the German philosopher Immanuel Kant (1724–1804). In his *nebular hypothesis* (in German *Allgemeine Naturgeschichte und Theorie des Himmels*, 1755) he postulated that the Solar System and the nebulae form periodically from a protonebula (in German ‘Urnebel’). The swirling nebula contracted into a rotating disk out of which, in the case of the Galaxy, stars contracted independently, as did the planets in the case of the Solar System. In 1796 the French mathematician Pierre Simon de Laplace, based on many new detections of fuzzy nebulae in the sky, formulated a similar hypothesis, which was long after referred to as the *Kant–Laplace Hypothesis*. There is a distinct difference between Kant’s and Laplace’s postulates. While Laplace takes possible effects of angular momentum into consideration. Kant remained more philosophical and envisaged a more universal mechanism which includes not only the Solar System but also features rudimentary concepts of today’s galaxies and concluded that formation is an ongoing and recurrent process [23].

This nebula hypothesis in its main elements was not well founded in terms of detailed physical descriptions and calculations. However, Kant could build on about 140 nebulous stellar objects known at the time through the works of C. Messier and F. Machain. The situation for Laplace was more comfortable as he could rely on F. W. Herschel in 1786, who created a list of over 1,000 such nebulae through

observations with his giant telescope. For over 100 years not much happened with respect to stellar formation and most efforts were directed to deciphering the structure of these nebulae. Of course, the hundred-year period of spectroscopic and photometric advances contributed much to the physical understanding of stars (see above). The 19th century was dominated by the discovery of several thousands of these nebulae, and in 1864 J. Herschel published the precursor of the *New General Catalog* which contained over 6,000 entries. Though at the time it was unknown, most of these entries were actually galaxies. A small fraction of these nebulae appeared peculiar in that they revealed a spiral nature. It was not until after the turn of the century that in 1936 E. Hubble's book *The Realm of the Nebulae* finally put an end to the discussion about the nature of the nebulae.

In the 19th century only one reference to stellar formation can be found which involves gravitation and thermal physics and this is the attempt by H. Helmholtz and W. Thomson (Lord Kelvin) to explain the energy radiated by the Sun through slow gravitational contraction (see Sect. 2.2.2). The start of the 20th century marked the beginning of intense activity to apply the laws of thermodynamics developed in the 19th century. At the forefront were contributions by J. Jeans, A. S. Eddington, and R. Emden. In his paper *The Stability of a Spherical Nebula* in 1902 Jeans first formulated what is known today as the *Jeans Criterion* describing the onset of gravitational instability of a uniform sphere of gas. After A. Einstein formulated his theory of special relativity in 1905, it was Eddington in 1917 who realized that the conversion of mass to energy could be key to the Sun's luminosity [24]. The physics of uniform gas spheres, specifically the mass versus luminosity relation of stars, was much debated, specifically between Jeans and Eddington. While Eddington published a series of manuscripts like *The Internal Constitution of Stars* in 1926 [25] or *Stars and Atoms* in 1927 [26] giving a first account of modern astrophysics, Jeans' work entitled *Astronomy and Cosmogony* in 1928 [27] is considered by many to be the first book on theoretical astrophysics. On the observational side contributions by J. Hartmann, H. Shapley, E. E. Barnard and many others shaped the perception of what is today referred to as the *interstellar medium* (see Chap. 3).

In the end it was Eddington who basically formulated the right idea, that the age of the Sun must be scaled by the ages of the oldest known sedimentary rocks and the main source of the star's energy must be subatomic. The formulation of thermonuclear fusion of hydrogen as the main energy source for stars by H. Bethe a decade later in 1938 confirmed Eddington's speculation [28]. Here S. Chandrasekhar's famous book entitled *An Introduction to the Study of Stellar Structure* in 1939 nicely summarizes these developments and is highly recommended for further reading [29]. Though the physical and mathematical ground work was set by Kant's Nebula Hypothesis, it was another 30 years before R. Larson (see Chap. 4) performed the first numerical calculations of a gravitational collapse. One decisive ingredient, though already identified in galactic clouds, was then introduced into the discussion: *dust*. The importance of dust in the context of stellar formation cannot be underestimated, a point emphasized by the title of this book.

2.2.2 *Understanding the Sun*

The Sun is the star everyone is most familiar with as it is directly involved in daily life (see Fig. 2.7). As the central star of our Solar System it provides all the energy for the Earth's biosystem. Without the steady inflow of light, all life would perish almost instantaneously and the Earth's surface would reduce to a cold icy desert. Radiation from the Sun regulates the oceans and the climate, makes plants grow, warms all living beings and stores its energy in the form of fossil resources. Sunshine, or the lack of it, even affects our moods.

The Sun is the closest star and its shape and surface can be observed with the naked eye once dimmed behind clouds or in atmospheric reflections during sunset. The earliest recording of dark spots on the Sun's surface are from Chinese records from 165 B.C., whereas the first sighting in Europe was recorded during 807 A.C. [15]. These records must have been forgotten and with great surprise, shortly after the invention of the telescope, Galilei and others observed these dark spots in stark contrast to what had been taught since Aristotle, that the Sun's surface is pure and without fault. The existence of these spots led to many theories and

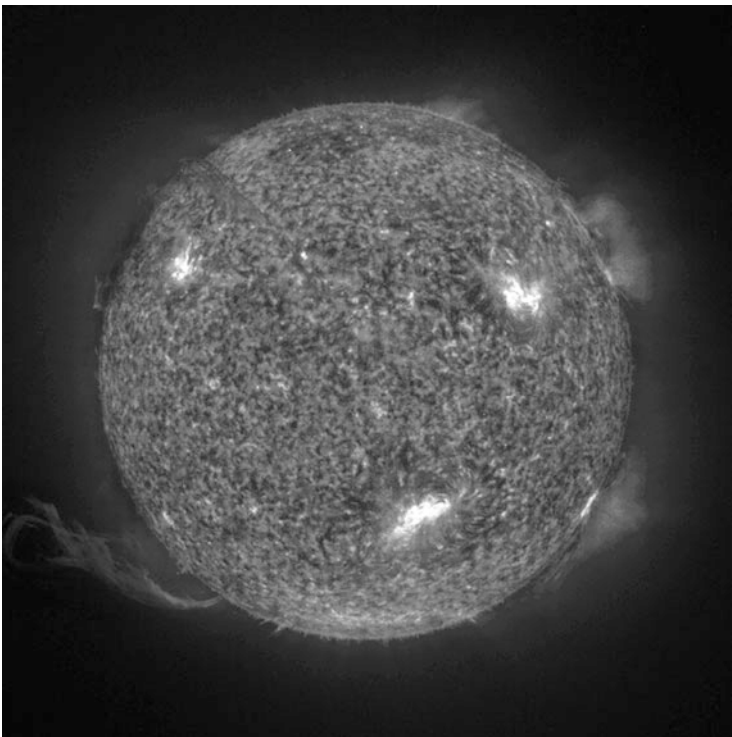


Fig. 2.7 The Sun as photographed by the solar observatory satellite SOHO at ultraviolet wavelengths. Credit: SOHO/ESA/NASA

speculations which ranged from interpretations such as solar mountain tops by G. Cassini to connections with climatic disasters like a devastating harvest in the 17th century by F.W. Herschel. However, the interest in Sun spots initiated a constant surveillance of the surface of the Sun, which led to the discovery by S. Schwabe in 1826 that these spots appear regularly on the Sun's surface and their abundance and strengths underlies an eleven year cycle. The study of these spots not only showed that the Sun is rotating, it also led to the determination of its rotational axis and the discovery by R. Carrington between 1851 and 1863 that the Sun's rotation varies between the poles and the equator. This fact is enormously important for understanding the Sun and stars, as it is characteristic of rotating gas spheres with a dense core. Furthermore it is indicative of the dynamo in the Sun's interior. Today it is known that the sunspot cycle even correlates with plant growth on Earth and from carbon dated tree rings it can be concluded that this cycle has persisted for at least 700 million years.

This time span as well as the projected age for the Earth's existence of billions of years ascertained from geological formations, were in stark contrast with estimates of the Sun's age put forth by theories explaining the origins of solar energy. These theories evolved at a time when physicists like S. Carnot, R. Mayer, J.P. Joule, H. von Helmholtz, R. Clausius and W. Thomson formulated the laws of thermodynamics, and the concept of conservation of energy emerged [30]. Concepts like a meteoric bombardment or chemical reactions were dismissed on the basis of either problems with celestial mechanics or of the projection that the Sun could not have been radiating for more than 3,000 years. By the middle of the 19th century von Helmholtz suggested that the Sun's heat budget was derived from contraction of an originally larger cloud. This theory had two advantages. First, it would provide tens of millions of years of energy. Second, the contraction rate of the Sun would be too small to measure and thus the idea would stay around. One hundred years later, when the nuclear chain reactions were discovered that transform hydrogen into helium under the release of unprecedented amounts of energy [28], the secret behind the Sun's energy source was finally identified. However, although in the end the contraction theory proved to be incorrect in explaining of the Sun's heat, it marked the first time that the process of gravitational contraction of a gas cloud was formulated in terms of detailed physical laws. Thus the lifetime of a star through gravitational contraction is called the *Kelvin–Helmholtz timescale* (see Sect. A.9).

2.2.3 What is a Star?

Since the developments during the 19th century and specifically since the systematic spectroscopic studies at the beginning of the 20th century, it has been recognized that the Sun and the stars are bodies of a kind. Although there is no simple definition of such an entity, a star has to fulfill at least two basic conditions to be recognized as such. It has to be self-bound by gravity, and it has to radiate energy which it produces in its interior. The first condition implies that there are internal forces that prevent the

body from collapsing under self-gravity. The body has to be approximately spherical as the gravitational force field is radially symmetric. Deviations towards obliqueness may arise through rotation. Internal forces can stem from radiation, heat motions, or lattice stability of solids just to name a few factors. If stability under gravity and symmetry were the only condition, then planets and maybe comets and asteroids could be stars as well. Comets and asteroids of course can be ruled out as modern imaging clearly show them to be non-spherical. Historically the view that these bodies are stars of some kind persisted for centuries, as expressions like ‘wandering star’ for planets or ‘guest stars’ in connection with comets still testify. It must be the second condition that makes a star: there has to be an energy source inside the star making it shine. Planets, although they appear as bright stars in the sky, cannot do that and their brightness is due to illumination from the Sun. Of course, no argument is perfect and the two largest planets in the Solar System, Jupiter and Saturn radiate more energy than the Sun provides, indicating that there is in fact an internal energy source. In this respect one has to add to the condition that the internal source also provides the energy to sustain the force against gravity.

2.2.4 Stars Evolve!

If the discovery that stars burn nuclear fuel had any consequence to star formation research it probably was the immediate realization that stars must evolve within a certain lifespan. To be more precise, while the star fuses hydrogen, it probably undergoes changes in its composition, structure, and appearance. As V. Trimble, an astronomer from the University of California, wrote in 2000 [31]:

Stars are, at least to our point of view, the most important building blocks of the universe, and in our era they are its major energy source. In 1900 no one had a clue how stars worked. By mid-century we had them figured out almost completely.

The developments in the 1930s from Eddington to Bethe indeed laid the ground work for an almost explosive development in the field of stellar structure and evolution. Specifically, stars had to evolve as a strong function of their mass. Key were hydrogen fusion lifetimes. From early calculations it was easily recognized that low-mass stars can burn hydrogen for billions of years. On the other hand, massive stars radiate energy at a rate which is many orders of magnitude larger than low-mass stars. Since their mass is only a few ten times larger this means that their fusion lifetime is much smaller. In fact, for massive O stars it is of the order of ten million years and less. Stars burn about 10% of their hydrogen and as a rule of thumb one can estimate the lifetime of stars by:

$$t_{life} = 7.3 \times 10^9 \frac{M/M_{\odot}}{L/L_{\odot}} \text{yr} \quad (2.2)$$

where M_{\odot} and L_{\odot} are the mass and luminosity of the Sun and M and L the same for the star [19]. Clearly, this development put an end to the perception that the Draper classification could resemble an evolutionary scale where early type O stars evolve into late type stars.

2.2.5 The Search for Young Stars

The short lifetimes of early type stars offers an opportunity to determine their birth places based on the argument that they could not have traveled far from their place of origin. As G. H. Herbig [32] remarks, it seems fairly surprising that the identification of stellar clusters containing OB stars as sites of on-going star formation did not occur until the early 1950s. By then A. Blaauw [33, 34] determined proper motions of early type stars with median velocities of 5 km s^{-1} with some showing peak velocities of $>40 \text{ km s}^{-1}$. Today the argument is even stronger as dispersion velocities of associated clouds have similar velocities (see Chap. 4) and net velocities of the stars relative to the parent cloud are usually less than 1 km s^{-1} (see [35]). An O star with 2 Myr of age would travel a distance of 2 pc; a fast one may reach 15 pc.

In 1947 B. Bok and his colleagues [36, 37] found small dark spots projected onto the bright H II region M8 and determined a size of less than 80,000 AU. The interpretation at the time was that these now called *Bok Globules* accrete matter from their environment and it is radiation pressure that forces them to contract. Bright H II regions, which of course contain O stars, would then have to be prime sites for stellar formation.

T Tauri stars were discovered in 1942 by A. H. Joy [38], but were not immediately identified as young stars. They got their name from *T Tau*, the first detected star of its kind. However, besides their strikingly irregular light curve, one obvious property was that they seem to be associated with dark or bright nebulosity [39]. Probably the first one to seriously suggest the notion that T Tauri stars are young, and not in these clouds by coincidence, was V. A. Ambartsumian [3] in 1947. It still took well into the 1950s until the fact was established [40, 41]. One of the earliest catalogs of young stars in star-forming regions was compiled by P. Parenago in 1955 [42]. But now help also came from the theoretical side. With the first calculations of positions of contracting stars in the HR-diagram in 1955 [43, 44] it became clearer that properties of T Tauri stars matched these predictions. In Fig. 2.6 a few examples are shown. Generally T Tauri stars possess significantly higher luminosities for their identified spectral class. According to C. Lada, decades later, these studies revealed that mature low-mass stars emerged from OB associations and were formed at a much higher rate than massive stars [45]. It was also suggested that star formation is still ongoing, even in the solar neighborhood.

The strong emission lines of T Tauri stars, specifically the Balmer H α line became their trademark in objective prism surveys, which scanned the sky up to

the late 1980s (see Sect. 6.3.2). The most systematic optical catalog of T Tauri stars was compiled in 1988 [46].

Today searches for young stars are pursued throughout the entire electromagnetic spectrum (see Sect. 2.3.1) as a result of the accelerating development of technologies. To be more specific, searches today are performed in the Radio, Sub-mm, IR, and X-ray bands (see Sects. 2.3.2 and 2.3.3).

2.3 Observing Stellar Formation

The fact that most research today is actually performed outside the optical wavelength band is for a very good reason. Collapsing clouds fully enshroud the newborn star within the in-falling envelope of dust and gas thus blocking the observer's view. Thus, if it were only up to the human eye and the spectral range it is sensitive to, then the process of stellar formation would be unobservable. In fact, as the course of the book will show, even if we could take a peek inside the collapse there might not be much to see as most radiation in the very early phases of the collapse happens at much longer wavelengths. The following three sections briefly outline the challenges that had to be overcome to finally reach broadband capability as well as to demonstrate the current and future technical advances necessary for stellar-formation research.

2.3.1 *The Conquest of the Electromagnetic Spectrum*

Newton, in the middle of the 17th century, found out that light is composed of a whole range of colors and that this spectrum spans from violet to blue, green, yellow, orange and red. It implies a wavelength range from about 400 to about 750 nanometers. Not much was known about the nature of light until 1690 when C. Huygens showed that light has a wave character. Over 100 years later this scale rapidly expanded at both ends. F.W. Herschel found in 1800 that the largest amount of heat from the Sun lies beyond the red color in the spectrum. One year later J. W. Ritter detected radiative activity beyond the violet color of the spectrum. Both events mark the discovery of infrared and ultraviolet light. J. Maxwell postulated in 1865 that light is composed of electromagnetic waves, a theory that was proved to be correct by H. Hertz in 1887, who also detected electromagnetic waves with very long wavelengths and thus added the radio band to the electromagnetic spectrum. In another milestone in 1905 W. C. Röntgen detected his *Röntgenstrahlung*, the mysterious X-rays which obviously rendered photoplates useless and which were able to penetrate soft human tissue. Seven years later *M. von Laue* finally demonstrated that these X-rays are electromagnetic waves of extremely short wavelengths. By then the wavelength range of the electromagnetic spectrum spanned from about 10^{-10} to 10^2 meters.

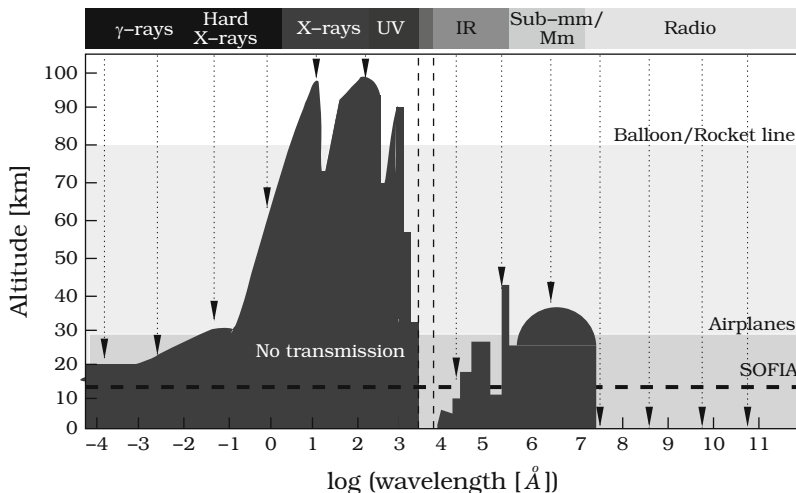


Fig. 2.8 The Earth’s atmosphere does not allow for penetration of light from the entire electromagnetic spectrum to the ground-based observer. Throughout the spectral band, absorption in the atmosphere dominates over transmission. The dark region marks the wavelengths and heights through which light cannot penetrate. Some wavelengths, like sub-millimeter radiation or X-rays are absorbed only to an intermediate height and can be observed with high-flying balloons. Adapted from Unsöld [19]

But the study of the nature of light so far was entirely confined to laboratory experiments. A similar conquest in the sky is an ongoing challenge. It requires high-flying balloons, rockets, and satellites as well as extremely sensitive electronic equipment. Electromagnetic radiation from stars and other cosmic objects can penetrate the Earth’s atmosphere only in limited fashion depending on its wavelength. Figure 2.8 shows schematically how only radio, optical, and some of the near-IR wavelengths have broad observing windows, while, for example, the UV range is almost entirely blocked out and X-rays can only be reached by high-flying balloons for short exposures. Sub-mm observations can be made from the ground at elevated heights, though most bands are entirely absorbed by the atmosphere’s water vapor.

2.3.2 Instrumentation, Facilities, and Bandpasses

Today searches for young stars are pursued throughout the entire electromagnetic spectrum as a result of the accelerating development of advanced technologies specifically for focal-plane instrumentation. Instrumental development is an essential part of stellar research, and astronomy in general always motivates the creation of new technologies. The goal is to gain increased sensitivity, increased spatial and spectral resolution, and increased wavelength coverage. Of course, one would like to achieve all this throughout most essential parts of the electromagnetic spectrum.

For a short review readers are directed to J. Kastner's review on imaging science in astronomy [10]. In star-formation research, observing efforts today engulf almost the entire spectral bandwidth from radio to γ -radiation. In essence, it took the whole second half of the 20th century to conquer the electromagnetic spectrum technologically in its entire bandwidth for star-formation research. The following offers a very limited review of the use of instrumentation over this time period, and for various wavelength bands without providing technical specifications, which are outside the focus of this book. More detailed explanations and a description of instrumental acronyms in the following sections and chapters can be found in Appendix F.

Observations of young stars are predominately performed in medium- to short-wavelength ranges:

Near-IR :	$3.5 \mu\text{m}$	$\lesssim \lambda \lesssim$	$0.8 \mu\text{m}$	<i>thermal continua, vibrational lines</i>
Optical :	$0.8 \mu\text{m}$	$\lesssim \lambda \lesssim$	$0.4 \mu\text{m}$ ($4,000 \text{ \AA}$)	<i>molecular/atomic lines</i>
Near-UV :	$4,000 \text{ \AA}$	$\lesssim \lambda \lesssim$	$1,000 \text{ \AA}$	<i>molecular/atomic lines</i>
Far-UV :	$1,000 \text{ \AA}$	$\lesssim \lambda \lesssim$	150 \AA	<i>atomic lines, continua</i>
X-ray :	150 \AA	$\lesssim \lambda \lesssim$	1 \AA	<i>inner shell atomic lines</i>

There are strong signatures at longer wavelengths as well but they are normally not understood in the context of the protostar itself. Dust envelopes around protostars are only visible in the far-IR and the sub-mm. Long wavelengths exclusively identify very young protostars in the context of thermal emission from dust and molecules and some non-thermal emission in the radio band [47]. Ranges are:

Radio :	50 m	$\lesssim \lambda \lesssim$	5 mm	<i>non-thermal continua rotational lines</i>
mm :	5 mm	$\lesssim \lambda \lesssim$	1 mm	<i>rotational lines, dust</i>
Sub-mm :	1 mm	$\lesssim \lambda \lesssim$	0.35 mm	<i>rotational lines, dust</i>
Far-IR :	$350 \mu\text{m}$	$\lesssim \lambda \lesssim$	$20 \mu\text{m}$	<i>rotational lines</i>
Mid-IR :	$20 \mu\text{m}$	$\lesssim \lambda \lesssim$	$3.5 \mu\text{m}$	<i>vibrational lines</i>

Optical telescopes can be used from the near-UV to the mm-bandpass. Observing capability is dominated by the transmission properties of the atmosphere and thus only a few windows outside the optical band are really visible from the ground, with some becoming visible at higher altitudes (see Fig. 2.8). At even higher altitudes IR and sub-mm waves become accessible, though mirror surfaces are increasingly sensitive to daytime to nighttime temperature changes and require specific accommodations. Thermal background noise irradiated by instrument components is reduced detector cooling. Throughout the IR band, variable thermal emission from the Earth's atmosphere is a problem growing with increasing wavelengths. Modern facilities thus use choppers or alternate beams to subtract atmospheric radiation and filter out the difference signal for further processing.

The 1940s and 1950s observed primarily older regions of stellar formation such as open clusters, OB, and T Tauri associations (see Sect. 2.2.5). The first systematic studies of young stars and star-forming regions were performed with optical telescopes. Though most of these studies occurred long after the 1950s when more advanced photomultipliers became available, hypersensitive photographic plates were used even into the early 1990s, which due to immense advances in photographic techniques had not much in common with the original plates [1]. To further enhance sensitivity the plates are sometimes submitted to a heating process (baking). The dynamical range of photographic plates is limited and so is their efficiency in comparison with photoelectronic devices. Thus some surveys used photographic plates specifically to cover wide fields, some used photoelectric detectors. Both methods produced uncertainties s ranging between 0.005 and 0.015 mag. Today large area charge-coupled devices (CCDs) with higher linear dynamic ranges and efficiencies have replaced most photographic plates. In order to obtain spectral information filter combinations [18] are applied. For higher resolution objective prism plates, objective grating spectrographs and slit spectrographs have been used [46, 48–53]. Objective prisms had already been used early in the century [21] and were specifically useful for scanning extended stellar fields. Today grating spectrographs are used with edged gratings for Cassegrain spectrographs and Coudé spectrographs that allow spectral resolutions of up to 100,000. Similar results can be achieved with lithographic reflection gratings in Echelle spectrographs [19, 54].

Many near-IR observations have been performed throughout the 1970s, notably [55–58], which together with optical observations provided a vital database for further studies of young stars. For wavelengths $\lesssim 3.5 \mu\text{m}$ nitrogen-cooled InSb-photodiodes are commonly used. Wavelengths $\lesssim 1.2 \mu\text{m}$ can be observed with optical photomultipliers, though nitrogen-cooled photo cathodes are needed.

Research in the 1980s also systematically began to survey star-forming regions in the mid-IR up to the mm-band as more advanced electronics became available. Specifically CO surveys provided a direct probe of molecular clouds and collapsing cloud cores (see Chaps. 3 and 4 for more details). For observations in the sub-mm and mm band nitrogen cooling becomes insufficient and superfluid helium cooling needs to be in place instead, forcing focal plane temperatures to below 2 K. S. Beckwith and collaborators, for example, used a He-cooled bolometer to measure 1.3 mm continuum emission with the *IRAM* 30 m telescope at an altitude of around 2,900 m on *Pico Valeta* in Spain [59]. The *IRAM* and *VLA* telescopes were used throughout the early 1990s to map molecular clouds, foremost the ρ Oph A cloud which hosts very recently formed stars with CO outflows [60]. Other surveys and observations of recently formed stars also involve dust emission from *Herbig Ae/Be stars* [61], objects in the ρ Oph cloud [62], H_2O emission in circumstellar envelopes of protostars [63], and from various collapsing cores with envelope masses $< 5 M_\odot$ [64], to name but a few out of hundreds of these observations performed to date.

Today many measurements are performed with *SCUBA* on the *JCMT*, which is a state-of-the-art facility located in Hawaii and which came into service in 1997.

Another even more recent sub-mm facility is the 10 m *HHT* on Mt. Graham in the USA. *ALMA* is a mm/sub-mm array of 50 antennas of 12 m diameter each located on the Chajnantor plain at 5,000 m altitude. Its design is driven by three key science goals:

- detect spectral line emission from CO or CII in galaxies at a redshift of $z = 3$
- image the gas kinematics in protostars and in protoplanetary disks in the nearest molecular clouds (150 pc)
- provide precise high dynamic range images at an angular resolution of 0.1 arcsec.

ALMA will become operational by 2012. Major recent, currently active, and future observing facilities like *CSO*, *BIMA*, and *OVRO* with short characterizations are listed in Appendix F.

2.3.3 *Stellar Formation Research from Space*

The benefits of space research with respect to stellar formation studies are undisputed. It should be noted, though, that space observatories are generally highly specialized, expensive, and usually suffer from much more limited lifetimes than their counterparts on the ground. In this respect modern star-formation research could not survive without the contributions of an armada of ground facilities equipped with instruments sensitive to ground-accessible wavelengths (see above). Specifically ground observations in the radio and sub-mm domain still contribute most to studies of molecular cloud collapse and very early phases in the star formation process.

On the other hand, there are domains where the exploration from space is not only highly beneficial, but is simply the only way to observe at all. The former is certainly true for bandpasses in the IR and sub-mm range, the latter is exclusively valid for the high energy domain. These two spectral domains have specifically been proven to be most valuable for investigating the properties of very young stars. Another advantage of in-orbit observations is that they provide long-term uninterrupted exposures as well as a much larger sky accessibility. And finally, observations from space offer the possibility to provide various deep and wide sky surveys on fast timescales. From the late 1970s, several observatories were launched into space which contributed to the understanding of early stellar evolution in major ways. Table 2.1 gives an account of all space missions with an agenda for star formation research that have been concluded or are still ongoing. It shows that there has been little X-ray coverage in the 1980s.

With the launch of the *X-ray observatory EINSTEIN* in late 1978 a new era in early stellar evolution began as X-rays were detected from young low-mass stars [65–67] soon after the observatory went into service and pointed at the Orion Nebula Cluster (ONC). X-rays from stars were not unheard of, X-ray stars in binary systems were known to possess X-ray emission much more powerful than that of the Sun. Also at about the same time, X-rays were also detected from hot massive

Table 2.1 Space missions relevant for star formation research. The bandpasses are generally given in wavelength units, except for X-ray missions that did not have high spectral resolving power. Here it is more common to specify the range in keV.

Mission	Bandpass spectral range	Mission dates	Major science impact in star-formation research
IUE	UV 1150–3299 Å	Jan. 78–Sep. 96	UV spectra of young massive stars, Herbig Ae/Be stars.
EINSTEIN	X-ray 1–20 keV	Nov. 78–Apr. 81	Detection of X-rays from low-mass stars.
IRAS	IR 8–120 μm	Jan. 83–Nov. 83	All-sky survey, photometry of young stars.
HST (Hubble)	Optical/IR 0.3–3.5 μm	Apr. 90–	High-resolution images of star-forming regions.
ROSAT	X-ray 0.1–2.4 keV	June 90–Feb. 99	First X-ray all-sky survey; identifications, distributions and luminosities of young stars.
EUVE	Far-UV 70–760 Å	June 92–Jan. 01	All-sky survey catalog, coronal spectra of stars.
ASCA	X-ray 0.3–10 keV	Feb. 93–July 00	Hard X-rays from star-forming regions.
ISO	IR/Sub-mm 2.5–240 μm	Nov. 95–May 98	High-resolution images and spectra of stellar cores young stars.
FUSE	Far-UV 905–1195 Å	June 99–Oct. 07	Molecular absorption lines in spectra of young stars.
Chandra	X-ray 1.5–160 Å	July 99–	High-resolution images and spectroscopy of star-forming regions, line diagnostics.
XMM-Newton	X-ray 6–120 Å	Dec. 99–	High-efficiency spectroscopy of young stars.
SST (Spitzer) 3–180 μm	IR/Sub-mm	Aug. 03–June 08	Imaging and spectroscopy of star-forming regions with high precision.
Herschel	Far-IR/Sub-mm	July 08– May 09–	Warm Imaging mission
SOFIA	2.2–26 μm	2011–	Star formation in galaxies, interstellar medium.
GAIA	Optical	Launch 2013	Permanent IR observatory flying at 13 km above ground.
JWST (James Webb)	Optical/IR	Launch 2018	3-D mapping of the Galaxy (ESA). Images beyond HST.

stars [68,69]. Here a plausible model for the X-ray emission from hot stars was soon on the table [70], whereas X-rays from young low-mass stars remained a mystery for much longer and even today high-energy emission is not fully understood ([71], see Chap. 10).

In the 1990s *ROSAT* [72] was the main X-ray observatory available for stellar evolution research. A model of the satellite in-flight configuration is shown in Fig. 2.9. It not only produced a large number of long exposed observations of star-forming regions but also conducted the first X-ray all-sky survey (Figure 2.10). This first survey provides a valuable resource for current and future missions and allows us to study wide distributions of young stars [73]. The currently active X-ray observatories *Chandra* (see Fig. 2.11) and *XMM-Newton* add a new quality to previous X-ray missions. One of them is the capability to perform high-resolution X-ray spectroscopy at resolving powers of 300 to 1,200. The high spatial resolution of *Chandra* with 0.5 arcsec adds another dimension to X-ray studies as the cores of dense very young stellar clusters, such as the Orion Nebula cluster, are now fully spatially resolved.

Space missions in the IR and sub-mm band took a similar path with time. The launch of *IRAS* in 1983, though its mission was only 10 months long, provided researchers with the first ever all-sky survey conducted in space in the IR. *IRAS* generated a database which still keeps researchers busy today, specifically for its



Fig. 2.9 Model of *ROSAT* in flight configuration. Throughout the 1990s *ROSAT* observed major star-forming regions in X-rays. One of its major accomplishments was the completion of the first X-ray all-sky survey (RASS). Credit: Max Planck Institut für extraterrestrische Physik

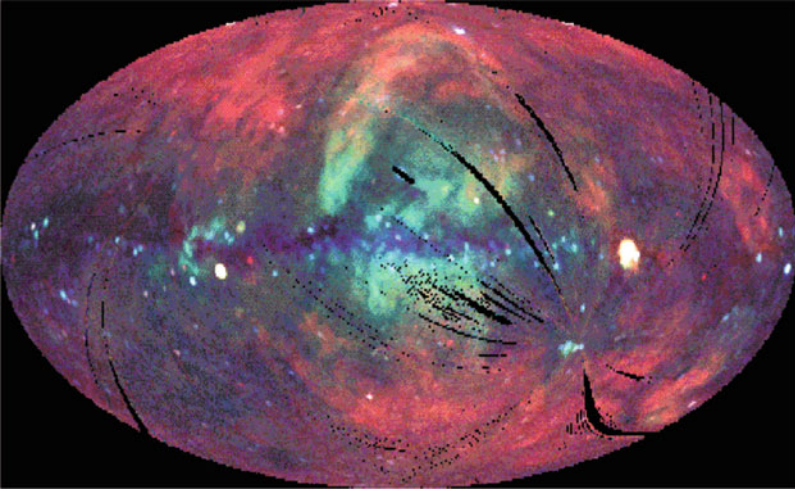


Fig. 2.10 The X-ray sky at energies between 0.1 and 2.4 keV as observed with the X-ray observatory *ROSAT* in the early 1990s. The colors represent X-ray energy, where red is near the low, blue near the high energy boundary. Credit: Max Planck Institute für extraterrestrische Physik



Fig. 2.11 Artist's impression of the *Chandra* spacecraft, which is orbiting Earth in a highly eccentric orbit (highest altitude is 139,000 km) since July 1999. Its currently projected tenure of operation leads into the year 2009. For more detailed information, see descriptions and links in Appendices E and F. Credit: NASA/CXC/SAO

wide field views. Missions with more powerful and higher precision instruments followed, like *ISO* in 1995 and *SST* in 2003. In its first 5 years in orbit the *SST* imaged the infrared sky with unprecedented precision at wavelengths between 3 and 180 micrometers with a large emphasis on star-forming regions providing the most detailed infrared data archive for decades to come.

This canonical development in the IR and X-ray bands is not accidental. Comparisons of *ROSAT* observations with IR images could demonstrate that observed activity in early evolutionary phases are quite complementary in these bands and their simultaneous study is highly beneficial. The vast improvements in observational quality in these two wavelength bands is demonstrated in Fig. 2.12. It shows four images of the Orion Nebula region centered on the *Orion Trapezium*

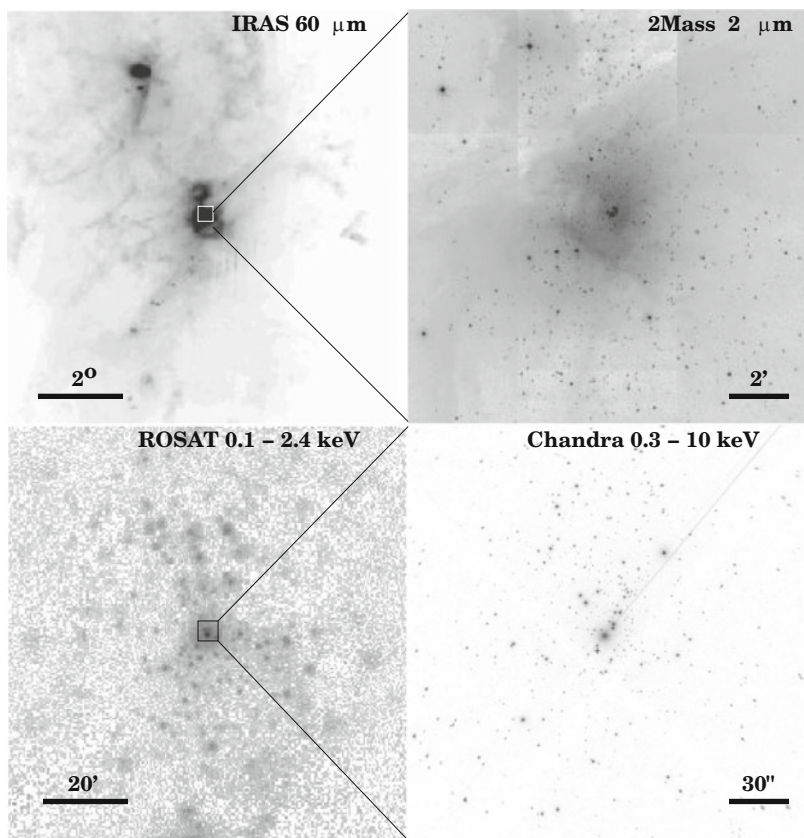


Fig. 2.12 (top left:) Wide view of the Orion region with *IRAS* at 60 μm . (top right:) Close-up view of the same region focusing on the center of the Orion Nebula with the *2MASS* observatory at 1–2 μm . (bottom left:) Wide view with the *ROSAT* PSPC in the X-ray band below 2.5 keV (above 5 \AA). (bottom right:) Close-up view with *Chandra* ACIS below 10 keV (above 1.2 \AA). The two comparisons illustrate the huge advances in the field of IR and X-ray astronomy, as well as the potential that exists to pursue wide-angle views as well as deep views

cluster. The very wide view of *IRAS* shows the large-scale structure of diffuse matter around the Nebula without being able to resolve many stars. The wide view of *ROSAT* shows that in X-rays only stars contribute to the emission. With a resolution of 25 arcsec of the *PSPC* (see Appendix F), however, *ROSAT* was still quite limited in resolving most point sources. In contrast the *2MASS* image shows highly resolved point sources as well as diffuse gas within the *IRAS* bandpass. The *2MASS* is a 2 μm on-ground survey observatory operated by the University of Massachusetts. Wide-view ground observations now always complement today's space observatories. Finally the *CHANDRA* view complements these IR observations with X-ray images of unprecedented resolution. All stars in the ONC with the exception of close binary systems are now fully resolved in the IR and X-ray domain providing researchers with a unique opportunity to study aspects of the early evolution of stars.

The future of star formation research from space is already well in progress. Table 2.1 mentions four exemplary missions, *SOFIA* as the successor of the airborne *Kuiper Observatory* of the 1980s and early 1990s, *JWST* (see Fig. 2.13) as the scientific successor to *Hubble*, and the space probes *Herschel* and *GAIA*. *SOFIA* began operations in mid-2010 and is providing astronomers access to optical, infrared, and sub-millimeter spectrum for the next two decades. It features a free-floating IR telescope mounted into the body of a jumbo jet, which will engage

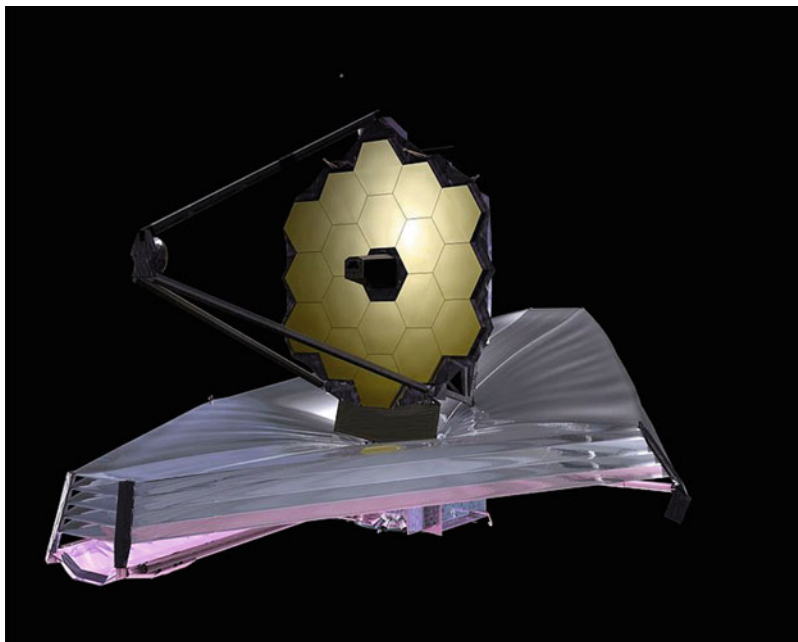


Fig. 2.13 Artist's impression of the *JWST* spacecraft, which will be launched around 2015 into one of the Earth-Sun Lagrangian points and will provide adaptive optics with a collecting area of 25 m². For more detailed information, see descriptions and links in Appendices E and F. Credit: NASA

in regular flights through the Earth's stratosphere, thus avoiding the absorbing effects of vapor clouds. *Herschel* was launched in 2009 and is to date the largest space telescope in operation featuring a 3.5 m Cassegrain telescope (see links in Appendices E and F). *Herschel* has the rather unique objective of studying the formation of galaxies in the early universe and thus provide information about the formation of stars in the early universe and clues toward cosmic star formation histories. *JWST* is to be launched during the second decade of the 20th century and with a collecting area of 25 m^2 in the near-IR band will be the largest telescope in space. Its primary scientific mission includes the search for light from the first stars, to study the formation and evolution of galaxies, stars, and planetary systems.

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