Astronomers' Universe

Neil English

Space Telescopes

Capturing the Rays of the Electromagnetic Spectrum

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Neil English
Fintry by Glasgow, United Kingdom

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Preface

Since the dawn of humankind, our species has sought to understand the nature of the universe around us and our place within it. For the vast majority of our history, we only had our immediate senses—sight, hearing, touch, taste, and a very limited sense of smell. On dark clear nights, huddled around a campfire, our ancestors gazed into the night sky, trying to make sense of the ever-changing view. Like the Sun and the Moon, the stars seemed to rise in the east and set in the west. Our ancestors noted the varying degrees of brightness of the stars in the sky, as well as their various hues—some red or orange, some yellow, and others white. And by carefully watching a few of the brighter luminaries, the most attentive sky gazers noticed that some of these stars wandered in their positions across the sky, sometimes disappearing altogether for months or years on end. These were called "planets," from the Greek word for wandering star, "planetos."

The invention of the telescope in Renaissance Europe ushered in a revolution in our understanding of the heavens that continues apace even today. Over four centuries, ground-based telescopes grew ever bigger and more powerful, but they could only see the universe in two principal wavebands—at visible light and at radio wavelengths. But advances in science were beginning to show that there existed other types of radiation—first infrared and then ultraviolet and more recently microwaves, X-rays, and gamma rays—all types of waves that are known collectively as electromagnetic radiation.

In order to see the universe at wavebands beyond the visible and radio parts of the electromagnetic spectrum, scientists had to find ways of penetrating the atmosphere, first by placing detectors on top of very high mountains where the air is thinner and then by using high-altitude balloons and sounding rockets, before the advent of the Space Age, when astronomers could finally build dedicated space-based missions with telescopes sensitive to the various parts of the electromagnetic spectrum blocked by our life-giving air. This is the story of that journey and the incredible new insights that transformed our knowledge of the cosmos utterly and forever. As well as being a story of human courage and single-mindedness, it also tracks the huge advances in technology humankind has enjoyed over the last century. In doing so, these space-based observatories have unveiled objects completely invisible to ground-based telescopes, demonstrating at once the beauty and the extreme danger of the space environment.

The book begins by taking a look at the science of waves, particularly electromagnetic waves, and their behavior and detection. In this opening chapter, we explore the source of much of the electromagnetic radiation in the cosmos—atoms. We'll survey the origin and nature of spectra and how this knowledge helps astronomers unravel a veritable treasure trove of new information about the chemical constitution and physical conditions of the stars and other astrophysical bodies generating them. Finally, we cover some basic astronomy that will help us fully engage with the science discussed in later chapters.

Chapter 2 recounts the incredible allegory of the Hubble Space Telescope, its perilous early days when engineers discovered its giant 96-inch mirror was misshapen, followed by its correction by NASA astronauts. We then explore the rich heritage of images captured by the world's most famous space telescope and how it completely transformed our understanding of the universe, both nearby and billions of light-years away.

We continue our exploration of the electromagnetic spectrum by chronicling the development of infrared (IR) astronomy and how space-based IR telescopes have allowed us to peer deep inside dust-laden star clusters and galaxies, hunting down a variety of cooler celestial objects invisible to even the largest optical telescopes. This chapter discusses important IR telescopes, including ROSAT and the Spitzer space telescope.

Next, we recount the fascinating story of the high-energy universe, beginning by exploring the shortest electromagnetic waves of all—gamma rays—and the extraordinary history of how scientists and engineers built better gamma ray detection systems, carrying them aloft on sounding rockets, as well as a host of sophisticated gamma ray space telescopes over many decades. These include early satellites such as Cos-B, Compton, BATSE, HETE, and more high-tech spacecraft including BeppoSAX, INTE-

GRAL, Swift, and Fermi. Here, we shall explore the mysterious nature of some of the most violent explosions in the universe: gamma ray bursts.

In the next chapter, we explore a waveband closer to the visible region of the electromagnetic spectrum—the ultraviolet universe. While a trickle of long-wave ultraviolet (UV) radiation can penetrate Earth's atmosphere, the vast majority of this radiation can only be detected in space. Space-based UV astronomy got a great boost in the 1970s with the launch of TD-1A and the Dutch ANS satellite. With the advance of technology, more sophisticated UV observatories came to the fore, with the International Ultraviolet Explorer (IUE) and the American-led Extreme Ultraviolet Explorer (EUVE), allowing astronomers to make great leaps forward in understanding a host of astrophysical phenomena from active galaxies, massive young stars, and even new insights into solar system objects.

X-rays have long provided us with a means of seeing the invisible, but it was not for several decades after their discovery that astronomers began to view the cosmos at these wavelengths. Of all the wavebands of the electromagnetic spectrum, it is arguably X-rays that have revealed the most insight into the physics of the Sun and hot OB and A stars. Astronomers have also discovered that cool, M dwarfs emit prodigious amounts of X-ray flares, calling into question whether the planets they harbor could ever sustain life. The earliest X-ray detectors were very primitive, but over the decades, they became increasingly more powerful. Accordingly, we shall explore key X-ray astronomical observatories, including the Orbiting Astronomical Observatory satellites, followed by more specialized missions, including Copernicus, Einstein, Uhuru, and Chandra.

Next, we return to wavelengths that are far too long to be seen by the human eye. The birth of microwave astronomy was essentially ground based, when in 1964 Arno Penzias and Robert Woodrow Wilson discovered the cosmic microwave background radiating almost uniformly across the entire sky. The significance of this serendipitous discovery cannot be overstated, since the unveiling has provided brand-new insights into how the universe must have begun. Described by Robert Gamow as the afterglow of creation, this radiation represents the remnants of the primordial fireball that characterized the hot Big Bang universe. The momentous discovery was followed up by the highly ambitious space missions COBE and, more recently, WMAP. These observatories gained glimpses into how galaxies and their constituent stars emerged from cosmic chaos and how their findings revolutionized our ideas about the origin and evolution of our universe.

By observing the universe across many wavebands, astronomers can gain a complete picture of the underlying nature of astrophysical bodies. It is arguably the Sun that has benefitted most from studies across the electromagnetic spectrum, and, in this capacity, we devote an entire chapter to how this knowledge was applied to our life-giving star and how the contributions made at visual, UV, X-ray, and gamma ray wavelengths have enabled us to piece together our most detailed picture yet of our life-sustaining Sun, with its dark spots, plages, flares, prominences, and much more. The collective data from across the EM spectrum has provided a more complex picture into the nature of the Sun and, by implication, other stars that inhabit the universe.

The era of precision astrometry, that is, the science of measuring the vast distances to the stars, entered a new era with the launch of the Hipparcos satellite, which cataloged 118,200 stars during a 4-year mission between 1989 and 1993. The spectacular success of Hipparcos was added to with the launch of the European Space Agency's Gaia spacecraft, the ongoing mission of which is to record the positions of up to one billion objects in the heavens in 3-D. In the last decade or so, astronomers have begun to employ orbiting satellites to hunt down and characterize a plethora of extrasolar planets, that is, planets orbiting other stars. We explore the recent success of the Kepler planet-finding mission, how it detects these planets, and the results of the surveys so far.

Finally, we end not with history but with the near future, by taking an in-depth look at the greatly anticipated replacement for the Hubble Space Telescope—the James Webb Space Telescope—which is widely expected to boldly go where no telescope has gone before.

Above all, however, the story of the history of space telescopes is one of human ingenuity, single-mindedness, collaboration, setbacks, and success—a microcosm of the human condition itself.

Fintry by Glasgow, UK Neil English

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Contents

1. Light: Nature's Great Information Superhighway

Humanity's curiosity about the cosmos stems from our ability to see. On a clear, dark night, our eyes can make out a few thousand bright pinpoints in the sky, stars located at great distances from Earth.

In this chapter, we shall explore the basic nature of light as understood by physicists, and explore how visible light is just one narrow window within a much broader phenomenon known as electromagnetic radiation.

Diligent investigation carried out over the centuries has established that light exhibits wavelike properties. Waves are oscillatory phenomena that carry energy and momentum through matter or empty space. All waves have a wavelength, that is, a fixed distance between successive crests or troughs. Wavelength is measured in meters. The number of whole waves passing a reference point in one second defines its frequency, measured in units called Hertz. Finally, all waves move through a medium with a certain velocity. This velocity is determined by multiplying the frequency by the wavelength. Light waves move at a speed of 300,000 km per second through the vacuum of space and at lower velocities through transparent materials (Fig. 1.1).

All waves exhibit a number of properties in common, including:

1. reflection
2. refraction
3. diffraction
4. interference

Reflection The reflection of waves is something we are aware of in our everyday lives. We look in the mirror and see our image. Sometimes we hear sound echoes. Both of these are examples of

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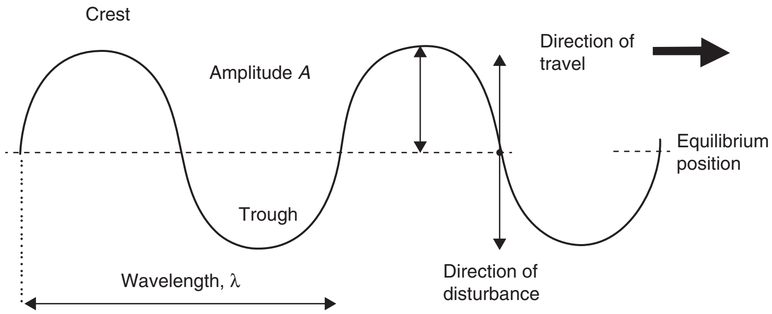

Fig. 1.1 The basic properties of a wave (Image by the author)

reflection. The reflection of waves makes possible the ability to bring waves to a precise focus, allowing us to see things that are quite invisible to the unaided eye. Reflection of waves enables great telescopes to see into the distant universe and permits our global technical civilization to exist via satellite communications.

Refraction When a wave enters a new medium such as glass or perspex, it slows down, and, unless it enters at right angles to the surface, it will change direction. This results in a bending of light that we call refraction. Refraction is the mechanism by which curved glass lenses can bring light to a precise focus. Different materials vary in their ability to bend light. Furthermore, a given transparent material bends different wavelengths of light by differing amounts. One way of quantifying this degree of bending is measured by a quantity known as the refractive index of the material. In general, the longer the wavelength, the lower the refractive index. The latter is responsible for the beautiful rainbow of colors seen when white light passes through a prism or a raindrop. Red light deviates least, and violet light, the most.

Diffraction When a wave passes an obstruction like a hill or through a gap, the wave spreads behind the regions that were obstructed. This is why radio waves can be detected behind buildings and hills. Such waves are said to be diffracted. If a wave is directed through a gap, it continues through that gap and spreads out into the area shielded by the gap. It follows that long waves are diffracted less than short waves, explaining why long radio waves can be picked up more easily inside a deep valley than shorter waves.

Interference Two waves with the same velocity, frequency and wavelength that hold their positions relative to each other are said to be coherent. Two kinds of interference are possible, constructive and destructive. When two waves meet each other in such a way that the peak of one wave meets a crest of the other, the waves 'add up' and create a locus of constructive interference. Conversely, when the crest of one wave lines up with a trough of another wave, they cancel each other out and exhibit so-called destructive interference. The interference of light is responsible for a number of everyday phenomena, including the pretty colors seen when oil floats on water or when a soap bubble floats in the air (Fig. 1.2).

Visible light is just one small part of what physicists refer to as the electromagnetic (EM) spectrum. Visible light consists of the red waves at the lowest frequency and violet light at the highest visible frequencies (Fig. 1.3).

Beyond the red light lie the invisible rays of infrared radiation. William Herschel is credited for having first discovered this radiation back in 1800, after demonstrating that a thermo meter placed just beyond the red end of the visible spectrum registered a temperature rise. Longer still are microwaves, which have an interesting story behind their discovery. While conducting research on radar, the American radar pioneer Percy Spencer found that a chocolate bar had melted in his shirt pocket. Further investigation

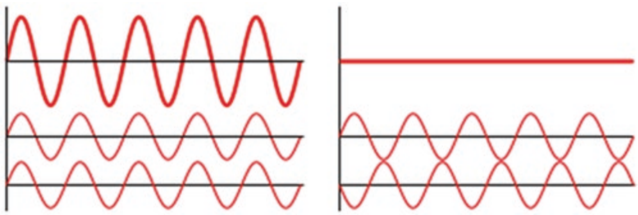

Fig. 1.2 Schematic showing constructive (*left*) and destructive (*right*) interference. The resultant effect is illustrated in the top waves (Image by the author)

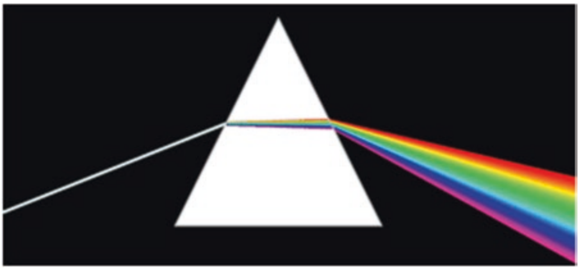

Fig. 1.3 When white light passes through a glass prism, a spectrum of colors is produced (Image by the author)

by Spencer showed that these 'heat rays' had wavelengths longer than infrared rays, and he called them microwaves. His experience inspired Spencer to invent the microwave oven.

Electromagnetic waves of even lower frequency are called radio and TV waves. Radio waves were first predicted by Scottish mathematical physicist James Clerk Maxwell in 1867. Maxwell noticed wavelike properties of light and similarities in electrical and magnetic responses. He then proposed equations that described light waves and radio waves as waves of electromagnetism that travel in space, radiated by a charged particle as it undergoes acceleration. In 1887, Heinrich Hertz demonstrated the reality of Maxwell's electromagnetic waves by experimentally generating radio waves in his laboratory. Many inventions followed, making use of these 'Hertzian' waves (another term for radio waves) to transfer energy and information through space.

If we venture beyond the violet, we encounter waves of ever increasing frequency from ultraviolet, X-rays and finally gamma rays. After hearing about Herschel's discovery of an invisible form of light beyond the red portion of the spectrum, the Polish scientist Johann Ritter decided to conduct experiments to determine if invisible light existed beyond the violet end of the spectrum as well. In 1801, he was experimenting with silver chloride, a chemical that turns black when it is exposed to sunlight. He had heard that exposure to blue light caused a greater reaction in silver chloride than exposure to red light. Ritter decided to measure the rate at which silver chloride reacted when exposed to the different colors of light. To do this, he directed sunlight through a glass prism to create a spectrum. He then placed silver chloride in each color of the spectrum. Ritter noticed that the silver chloride showed little change in the red part of the spectrum, but increasingly darkened at the violet end of the spectrum. This showed that exposure to blue light did cause silver chloride to turn black much more efficiently than exposure to red light.

Ritter then decided to place silver chloride in the area just beyond the violet end of the spectrum, in a region where no sunlight was visible. To his amazement, he saw that the silver chloride displayed an intense reaction well beyond the violet end of the spectrum, where no visible light could be seen. This showed for the first time that an invisible form of light existed beyond the violet end of the visible spectrum. This new radiation, which Ritter called 'chemical rays,' later became known as ultraviolet light or ultraviolet radiation; 'ultra' meaning beyond. Ritter's experiment, along with Herschel's discovery, proved that invisible forms of light existed beyond both ends of the visible spectrum.

In late 1895, a German physicist, W. C. Roentgen, was working with a cathode ray tube in his laboratory. He was working with tubes similar to contemporary fluorescent light bulbs. He evacuated the tube of as much air as possible, replaced it with a special gas, and then passed a high electric voltage through it. When he did this, the tube would produce a fluorescent glow. Roentgen shielded the tube with heavy black paper and found that a green-colored fluorescent light could be seen coming from a screen sitting a few feet away from the tube. He realized that he had produced a previously unknown "invisible light," or ray, that was being emitted from the tube—a ray that was capable of passing through the heavy paper covering the tube. Through additional experiments, Roentgen also found that these new rays would pass through most substances, casting shadows of solid objects on pieces of film. In mathematics, chemistry and other areas of study, "X" is used to indicate an unknown quantity, so he named the new rays X-rays.

Further experiments conducted by Roentgen found that X-rays would pass through living tissue, rendering bones and metals visible. One of Roentgen's first experiments late in 1895 was a film of his wife Bertha's hand with a ring on her finger. The news of Roentgen's discovery spread quickly throughout the world. Scientists everywhere could duplicate his experiment because the cathode tube was very well known during this period. By early 1896, X-rays were already being utilized clinically in the United States to investigate such things as bone fractures and other kinds of wounds.

The first gamma ray source to be discovered was through the radioactive decay of a substance. When a substance radioactively decays, an excited radioactive nucleus emits a gamma ray, and the resulting nucleus is more stable. Paul Villard, a French chemist and physicist, discovered gamma radiation in 1900 while studying radiation emitted from radium. Villard knew that his described radiation was more powerful than previously described types of rays from radium, which included beta rays, first noted as "radioactivity" by Henri Becquerel in 1896, and alpha rays, discovered as a less penetrating form of radiation by Rutherford in 1899. However, Villard did not recognize them as a fundamentally new type of electromagnetic radiation. This was accomplished by Ernest Rutherford, who in 1903 named Villard's rays "gamma rays" by analogy with the beta and alpha rays that Rutherford had differentiated in 1899. The "rays" emitted by radioactive elements were named in order of their power to penetrate various materials, using the first three letters of the Greek alphabet: alpha rays as the least penetrating, followed by beta rays, followed by gamma rays as the most penetrating. Rutherford also noted that gamma rays were not deflected (or at least, not easily deflected) by a magnetic field, another property distinguishing them from alpha and beta rays.

Although EM waves exhibit different frequencies (and hence wavelengths), they all move at the same velocity through a given material, as described by Maxwell's famous equations. Figure 1.4 shows the relative positions of these various forms of EM radiation.

In the dawning years of the twentieth century, scientists uncovered new phenomena about the nature of light that could best be explained if light and other forms of EM radiation acted like a particle and not a wave. Perhaps the best attested example of this is the photoelectric effect. When light of a given frequency is shone onto a polished metal surface, it develops a positive electric charge. This is due to the ejection of negatively charged electrons from the metal atoms near its surface. Moreover, only light with a frequency at or above the so-called threshold frequency can elicit the effect.

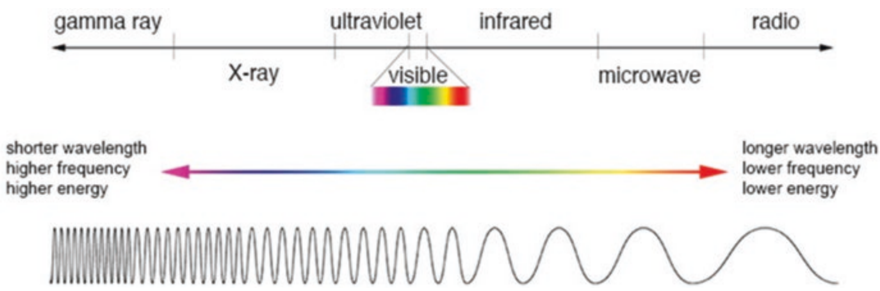

FIG. 1.4 The electromagnetic spectrum (Image by the author)

If the light that shines on the metal has a frequency below the threshold frequency, no photoelectric effect is seen, no matter how intense the light source or how long one irradiates the metal surface. These strange results can be interpreted as light behaving like tiny packages of energy or 'photons,' more like bullets than waves. Moreover, the energy of a photon is directly proportional to its frequency; the higher the frequency, the higher the energy of the photon. That's why visible light doesn't cause sunburn while higher energy (higher frequency) ultraviolet light does. It also explains why higher frequency X-rays and gamma rays are even more dangerous to living things.

German physicist Max Planck built on this work. Planck derived a law for the spectrum of black body radiation. A black body is an object that absorbs all the radiations that is incident upon it (it reflects no radiation) and radiates energy that is only from the object itself. An example of a black body is a furnace with walls that absorb all incident radiation but has a very small opening for radiation from inside the furnace to escape. Wilhelm Wien derived a simple formula that predicts the temperature of any such body from knowing its peak wavelength (Lambda) output. Specifically:

$$\text{Lambda Peak}\left(\text{in meters}\right)\times T = 2.889\times10^{-3}$$

Wien's displacement law allows astronomers to compute the temperature of any black body (of which stars approximate very well) if we know the wavelength at which the body emits its peak wavelength. In effect then, Wien's displacement law enables us to measure the temperature of any black body source, thereby acting as a cosmic thermo meter! Wien's law shows us that the hotter the body's temperature, the more it moves to shorter wavelengths (higher frequencies). For example, our Sun radiates its peak wavelength at 500 nm. Plugging this into Wien's formula and rearranging for T gives 5778 K. Cooler stars have their peak wavelengths shifted to the red end of the visible spectrum, while hot-white and blue-white stars display their peak wavelengths in the blue and violet part of the visible spectrum (Fig. 1.5).

Human ingenuity has enabled us to build instruments that can detect all forms of electromagnetic radiation, from ultra-short wave gamma rays through the visible spectrum and on through the infrared, microwave and radio regions of the EM spectrum. Infrared, microwaves and radio waves can be focused using curved parabolic surfaces. The larger the wavelength, the larger the size of the dish needed to collect and focus those waves. Ultraviolet radiation can also be focused by telescopes in the same way that they collect visible light.

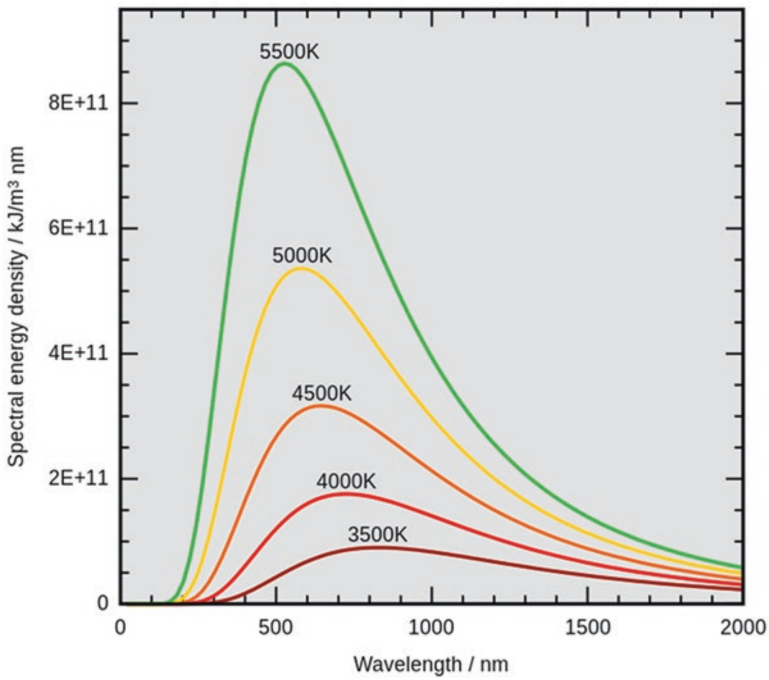

Fig. 1.5 Wien's law—the hotter the object the more its peak wavelength shifts to shorter wavelengths (Image by the author)

However, focusing shorter wave radiation—X-rays and gamma rays—requires a different kind of technology to that employed for other parts of the EM spectrum. These high energy photons cut right through regular mirrors. The rays must be bounced off a mirror at a very low angle if they are to be captured. This technique is referred to as grazing incidence. For this reason, the mirrors in X-ray telescopes are mounted with their surfaces only slightly off a parallel line with the incoming X-rays. Application of the grazing-incidence principle makes it possible to focus X-rays from a cosmic object into an image that can be recorded electronically (Fig. 1.6).

Several types of X-ray detectors have been devised, including Geiger counters, proportional counters, and scintillation counters. These detectors require a large collecting area because celestial X-ray sources are remote and so are almost invariably weak; thus a high efficiency for detecting X-rays over the cosmic ray-induced background radiation is required. Although astronomers using visible and UV telescopes typically adopt familiar concepts such as wavelength or frequency to describe the range of EM radiation that they are sensitive to, X-ray and gamma ray telescopes make use of another unit—the electron volt (eV). One electron volt is equivalent to 1.6×10^{-19} joules. In general, X-ray telescopes cover an energy range between 1 keV to 10 MeV, while their gamma ray counterparts monitor higher energy radiations up to several tens of GeVs. In addition, astronomers refer to

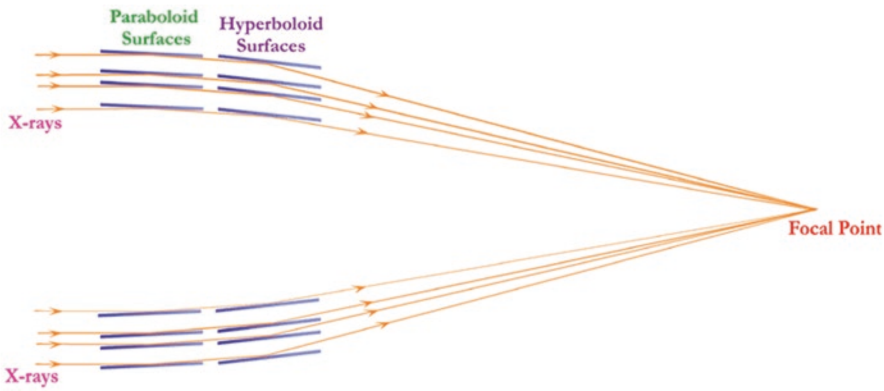

Fig. 1.6 X-ray and gamma ray telescopes focus rays by reflecting them off mirrors at very shallow angles (Image by the author)

higher energy radiations as 'hard,' while those wavebands with less energy are said to be 'soft.' On our journey through the history of space telescopes, we will occasionally encounter a less commonly used unit of energy called the erg. One erg is the equivalent of 10^{-7} joules. Thus, power output can also be expressed in units of ergs per second.

Now that we have briefly surveyed the properties of EM radiation, it is time to look at the kind of scientific work these telescopes can accomplish in the vacuum of space. Space is a hostile place. Earth's atmosphere provides a protective blanket to shield surface life forms from the deadly rays emanating from a variety of celestial sources. The atmosphere allows visible light and radio waves to pass through it, but blocks the majority of infrared radiation, ultraviolet, as well as deadly X-rays and gamma rays. For these reasons, the majority of space telescopes are dedicated to imaging these radiations.

Turbulence in Earth's atmosphere can distort the images produced by large optical telescopes, even those placed at a very high elevation. As a result, astronomers have sought to launch optical telescopes into the vacuum of space in search of the clearest images of the cosmos possible. The Hubble Space Telescope, discussed at length in a later chapter, is the most celebrated example from this genre. By imaging celestial objects in different regions of the EM spectrum, astronomers can glean far more information than they could if they restricted their studies to the visible wavelengths (Fig. 1.7).

As well as imaging objects both within and beyond our own Solar System, starlight reveals far more information when subjected to spectroscopic study. By passing light through a high-resolution diffraction grating, astronomers can unravel the chemical composition of the star with high precision. In addition to its bulk chemical constitution, the temperature, space velocity, magnetic field strength, and even the tell-tale signs of planets orbiting their parent stars can be studied. In the chapters that follow, we shall explore how telescopes launched into Earth orbit and beyond peer into the deep universe with eyes sensitive to different parts of the EM spectrum. The mind still boggles at what they have seen, as later chapters shall reveal.

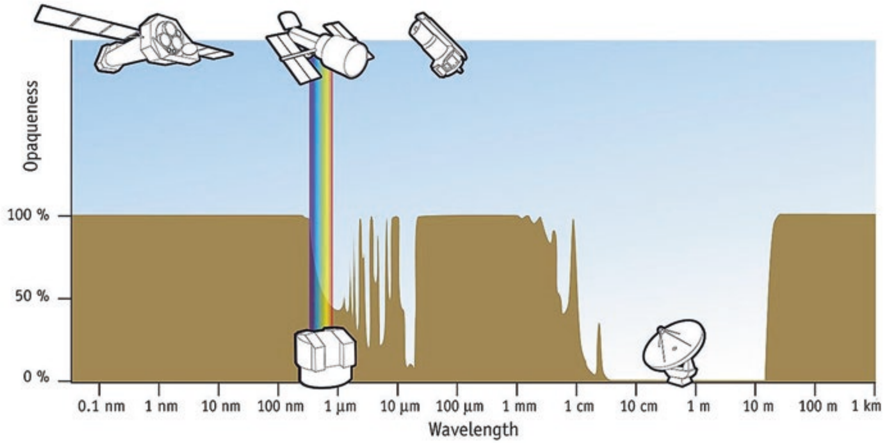

Fig. 1.7 This shows the opaqueness of Earth's atmosphere to various parts of the EM spectrum (Image credit: ESO)

Divining the Chemistry of the Stars

One of the best examples of false prognostications regarding the limits of science, in this case astrophysics, was made in 1835 by the prominent French philosopher Auguste Comte. In his *Cours de Philosophie Positive* he wrote:

> On the subject of stars, all investigations which are not ultimately reducible to simple visual observations are … necessarily denied to us. While we can conceive of the possibility of determining their shapes, their sizes, and their motions, we shall never be able by any means to study their chemical composition or their mineralogical structure … Our knowledge concerning their gaseous envelopes is necessarily limited to their existence, size … and refractive power, we shall not at all be able to determine their chemical composition or even their density… I regard any notion concerning the true mean temperature of the various stars as forever denied to us.

However, only 14 years later, the physicist Gustav Kirchhoff discovered that the temperature and chemical composition of a gas could be deduced from its electromagnetic spectrum viewed from an arbitrary distance. This method was extended to astronomical bodies by Huggins in 1864, using a spectrograph attached to a telescope. Not only have we learned how to determine the chemical composition of the stars and nebulae, but the element helium (the second most abundant in the universe) was first identified in the spectrum of the Sun, rather than in an earthbound laboratory.

Today, astronomers use spectroscopy to measure chemical abundances, temperatures, velocities, rotation rates, ionization states, magnetic fields, pressure, turbulence, density, and many other properties of distant planets, stars, and galaxies. Some of the objects studied this way are over 10 billion light years away. Spectroscopy is a study that yields rich information about the universe. And within a laboratory framework, spectroscopy provided the experimental basis for the most accurate science we know of: quantum mechanics.

When a body is heated, and it becomes more energetic, it will begin to emit visible light. In the early nineteenth century, physicists were aware that the light from the Sun was missing wavelengths characterized by dark lines in the resulting emission spectrum. These were called Fraunhofer lines after the German physicist and optician Joseph Von Fraunhofer, who discovered and recorded in excess of 500 of them.

Around the same time, chemists such as Robert Bunsen (among others) began examining the light emitted by chemical elements when heated in a laboratory flame. When this light was passed through a spectrometer to more closely analyze the spectrum produced, it showed that it was made up of a series of discrete lines. Each series was unique to a particular element and could thus be used as a type of 'signature' to determine the element's presence. The visible spectrum of the element hydrogen is shown in Fig. 1.8.

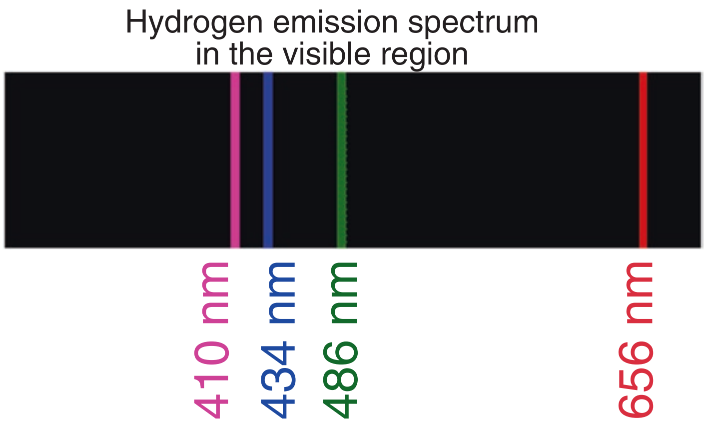

Fig. 1.8 The visible spectrum of hydrogen (Image credit: University of Texas)

When chemists unraveled more about the nature of the atom, they discovered that the more complex atoms also had more complex spectra. Illustrated below are the visible spectra of carbon, nitrogen, and oxygen. It became clear that the 'missing' lines in the Sun's continuous emission spectrum were matched with the emission lines of individual elements, which could be measured here on Earth. As a result, it was proposed that the white light being emitted by the surface of the Sun was passing through its atmosphere of chemical elements, which were only absorbing the wavelengths that somehow characterized their structure. This discovery led to many further questions. For one thing, why do the wavelengths generated by hydrogen differ from those absorbed by another chemical element such as iron or zinc? What's more, why is it that only these special wavelengths are being absorbed or emitted to the exclusion of all the others? The answers to these questions had to wait 60 more years to be addressed and required the work of great theoretical physicists, such as Max Planck, Albert Einstein, and Niels Bohr.

Einstein developed Planck's work on black body radiation and proposed that, at the smallest level, light was delivered in packets of energy called photons. Each particle carried a fixed amount of energy given by the equation $E = hf$, where E represents energy, h is Planck's constant, and f is the frequency of the light considered. This means that each photon of light absorbed or emitted by an atom has a particular, unique energy.

Bohr's model of the hydrogen atom uses this fact and Rutherford's nuclear atomic model to propose that electrons orbit a dense, positively charged nucleus in a manner similar to planets orbiting a star. The radius of the orbit is determined by the electrical potential energy of the electron in the electric field created by the nucleus. As the electrons are attracted to the nucleus, work needs to be done to move them further away and so larger radius orbits are higher-energy states. More significantly, only particular energy states are permitted. In other words, these orbits are quantized. This means that only certain, particular orbit radii can be maintained.

To jump from a low energy state to a high energy state requires the electron to absorb exactly the right amount of energy from an incoming photon. This is known as an electron excitation with the electron being promoted to a higher energy state. Conversely, if an electron falls from an excited state to a lower state, it will emit a photon whose energy will correspond exactly to an energy gap in the two states.

The proposal to restrict the energy states to a limited set of discrete values explains the observed absorption and emission spectra. The characteristic lines or wavelengths emitted or absorbed (missing) correspond exactly to the energy gap in the two electron states. As different elements contain different numbers of positively charged protons in the nucleus (and hence the number of electrons in the orbits), the exact values for the energy states and their differences are unique to those elements (Fig. 1.9).

The spectral lines are not restricted to visible wavelengths. Many other lines were uncovered in different parts of the EM spectrum. Thus, scientists could use visible, infrared, UV, X-ray, and even gamma ray spectroscopy to divine further secrets of the composition and physical properties of celestial objects.

Though it is beyond the scope of this text to discuss the full panoply of details that spectroscopy reveals about a luminous body, it is enough to say the study reveals an enormous amount of detail about the temperature, surface gravity, mass, ionization state of its constituent matter, motion (especially the Doppler effect, discussed briefly in the next section of this chapter), and magnetic field strength of the celestial body. Spectroscopy may even enable astronomers to sniff the chemistry of the atmospheres of planets orbiting other stars. We could then identify whether life could exist on these planets! We shall explore these details in later chapters while discussing specific space telescope missions (Fig. 1.10).

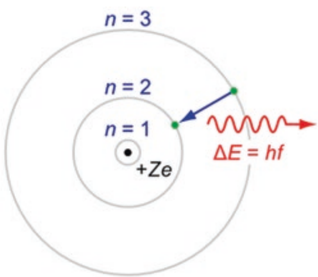

Fig. 1.9 The three lowest electron orbital states permitted in the Bohr model of the hydrogen atom (Image credit: Jabberwok)

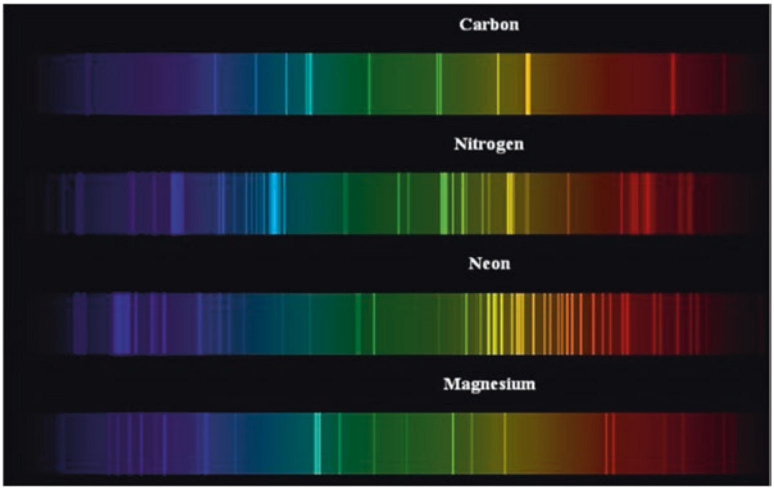

Fig. 1.10 The emission spectra in visible light for some common elements (Image credit: spiff.rit.edu)

Electromagnetic Waves and Motion

The history of this subject began with the development in the nineteenth century of the theory of wave mechanics and the exploration of phenomena associated with the Doppler effect. Imagine you are watching an ambulance approach you at high speed with its siren blasting. As the sound waves are moving with their own velocity, the waves are compressed in the direction of motion, causing their frequency (pitch) to increase. Conversely, as the ambulance recedes from you, the waves are stretched out and their pitch accordingly decreases. This effect was named after the Austrian scientist, Christian Doppler (1803–1853), who offered the first known physical explanation for the phenomenon in 1842. The hypothesis was tested and confirmed for sound waves by the Dutch scientist Christophorus Buys Ballot in 1845. Doppler correctly predicted that the phenomenon should apply to all waves, and in particular, suggested that the varying colors of stars could be attributed to their motion with respect to Earth. Specifically, pitch is to sound as color is to light. Before this was verified, however, it was found that stellar colors were primarily due to a star's temperature, not motion. Only later was Doppler vindicated by verified redshift observations.

The first Doppler red shift was described by French physicist Hippolyte Fizeau in 1848, who pointed to the shift in spectral lines seen in stars as being due to the Doppler effect. If the star is moving away from us, then the spectrum of Fraunhofer lines would be shifted to lower frequencies, that is, 'red-shifted.' Conversely, if the star is moving towards a stationary observer, those same spectral lines shift to higher frequencies, that is, 'blue-shifted.'

The physical quantity called red shift (z) is provided by the simple formula:

$$z = (\text{Lambda}(\text{observed}) - \text{Lambda}(\text{rest})) / \text{Lambda}(\text{rest})$$

Furthermore, for stars or galaxies moving at speeds much less than the speed of light, the velocity of the star (v) can be calculated using the formula:

$$v = zc$$

where c is the speed of light in a vacuum (300 million meters per second). The effect is sometimes called the Doppler-Fizeau effect.

In 1868, British astronomer William Huggins was the first to determine the velocity of a star moving away from Earth by this method. In 1871, optical red shift was confirmed when the phenomenon was observed in Fraunhofer lines using solar rotation, about 0.01 nm in the red. In 1887, Vogel and Scheiner discovered the annual Doppler effect, the yearly change in the Doppler shift of stars located near the ecliptic due to the orbital velocity of Earth. In 1901, Aristarkh Belopolsky verified optical redshift in the laboratory using a system of rotating mirrors.

The earliest mention of the term "red shift" in print (in hyphenated form) appears to be by American astronomer Walter S. Adams in 1908, when he mentions, "Two methods of investigating that nature of the nebular red-shift." The word does not appear unhyphenated until about 1934 by Willem de Sitter, perhaps indicating that up to that point its German equivalent, *Rotverschiebung*, was more commonly used.

In 1912, Vesto Slipher, then based at Lowell Observatory in Flagstaff, Arizona, discovered that most spiral galaxies, which were mostly thought to be spiral nebulae, had sizable red shifts. Slipher first documented his measurement in the very first volume of the

Lowell Observatory Bulletin. Just a few years later, he wrote a review in the journal *Popular Astronomy.* In it he states, "…the early discovery that the great Andromeda spiral had the quite exceptional velocity of –300 km/s showed the means then available, capable of investigating not only the spectra of the spirals but their velocities as well." Slipher reported the velocities for a total of 15 spiral nebulae from across the night sky, 12 of which having observable "positive" (that is, recessional) velocities. Just over a decade later, Edwin Hubble discovered an approximate relationship between the red shifts of such 'nebulae' and the distances to them with the formulation of the famous law that bears his name; Hubble's law. These observations vindicated Alexander Friedmann's 1922 work, in which he derived the groundbreaking equations still used by cosmologists today. Together, they are considered robust evidence for an expanding universe and the Big Bang theory.

The Zeeman Effect

As well as providing information about the chemistry and speed of astronomical objects, spectra can also be used to measure the intensity of magnetic fields in the body under study.

This can be achieved through a process called the Zeeman effect, which involves the splitting of a spectral line by a magnetic field. Any single atomic spectral line under normal conditions would be split into two in the presence of a magnetic field, one of lower energy and one of higher energy in comparison to the original line. The detailed explanation for the Zeeman effect requires some understanding of quantum physics, which need not concern us further here apart from stating that the strength of the magnetic field inside a star can be measured using this technique (Fig. 1.11).

A Brief Look at the Lives and Classifications of Stars

In astronomy, stellar classification involves grouping stars together based on their spectral characteristics. The spectral class of a star gives clues about the temperature of its atmosphere. Most stars

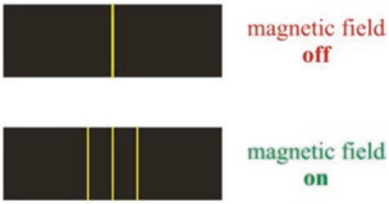

Fig. 1.11 The Zeeman effect occurs when spectral lines are split due to being subjected to a magnetic field (Image credit: www.periodni.com)

are currently classified using the letters O, B, A, F, G, K, M, and L, in order of increasing coolness. The hottest spectral classes (O, B, and A) have a blue-white or white color, those of intermediate spectral class (F and G) are yellow-white, K stars are orange, and M-type stars shine with a red hue. L-type stars, which are legion in the galaxy, shine most strongly, not in visible light, but in the infrared.

Our Sun, a G-type star, formed about 4.6 billion years ago and is now about half way through its life. Research has shown that during this epoch, the levels of the radioactive elements—uranium and thorium—essential for building planets and plate tectonics, were at their highest. Moreover, there is now evidence that the solar nebula—that great cloud of gas and dust out of which the Sun and its retinue of planets formed—were enriched by an eclectic mix of elements from not one but two types of stellar explosions (supernova events). These exploding stars were not so close as to destroy the solar nebula, but neither were they so far away as to make no difference to its final chemical constitution. How uncanny!

Scientists have discovered many different kinds of stars—from white dwarfs to supergiant stars. But up until the early 1900s, there was no general way to classify them. All of that changed with the invention of the Hertzsprung-Russell (H-R) diagram, which has become one of the most important tools in stellar astronomy. You could say the H-R diagram is to astronomers what the Periodic Table of Elements is to chemists.

Independently, Danish astronomer Ejnar Hertzsprung and the American astronomer, Henry Norris Russell, discovered that when they compared the luminosity with the type of light that was observed from stars, there were many patterns that emerged.

In 1905, Hertzsprung presented tables of luminosities and star colors, noting many correlations and trends. In 1913, Russell published similar data in a diagram. It is now called the Hertzsprung-Russell diagram in honor of these two pioneers. Russell noticed that almost 90 % of the stars fell along a diagonal ribbon that stretched from the top left to the bottom right of his diagram. The stars that fell onto this diagonal ribbon were classified as being on the "main sequence," of which our Sun is a member (Fig. 1.12).

They also noticed that other groups of stars become evident, such as blue supergiants to the upper right and white dwarfs to the lower left of the main sequence. O, B, and A stars are sometimes called "early type" while K and M stars are said to be "late type." This stems from an early twentieth century model of stellar evolution in which stars were powered by gravitational contraction via the Kelvin-Helmholtz mechanism. It was thought that stars were initially hot and bright (early type) and gradually evolved to become cool and dim (late type). The Kelvin-Helmholtz mechanism is an

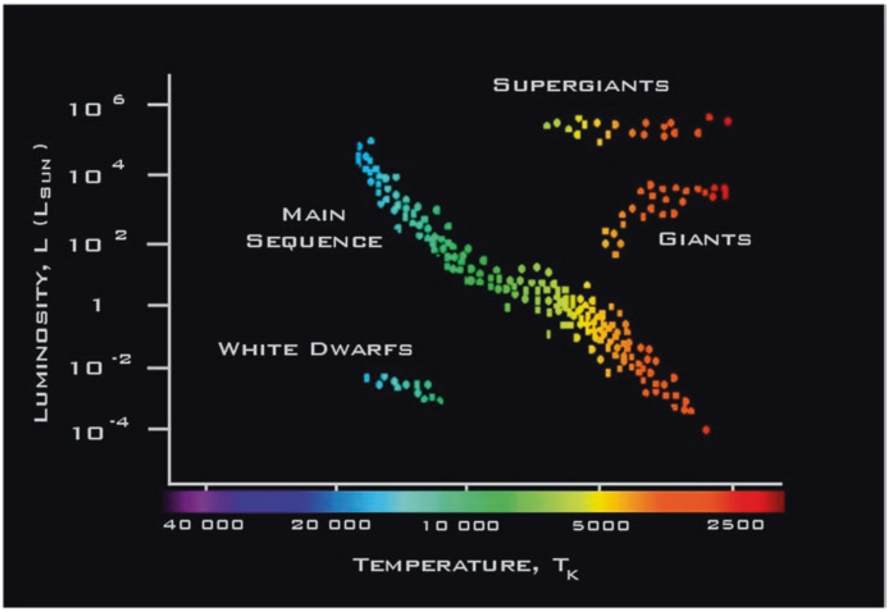

Fig. 1.12 The Hertzsprung-Russell diagram showing the main sequence (*diagonal line*) and some of the main groups of stars that lie off of it (Image credit: www.ie.ac.uk)