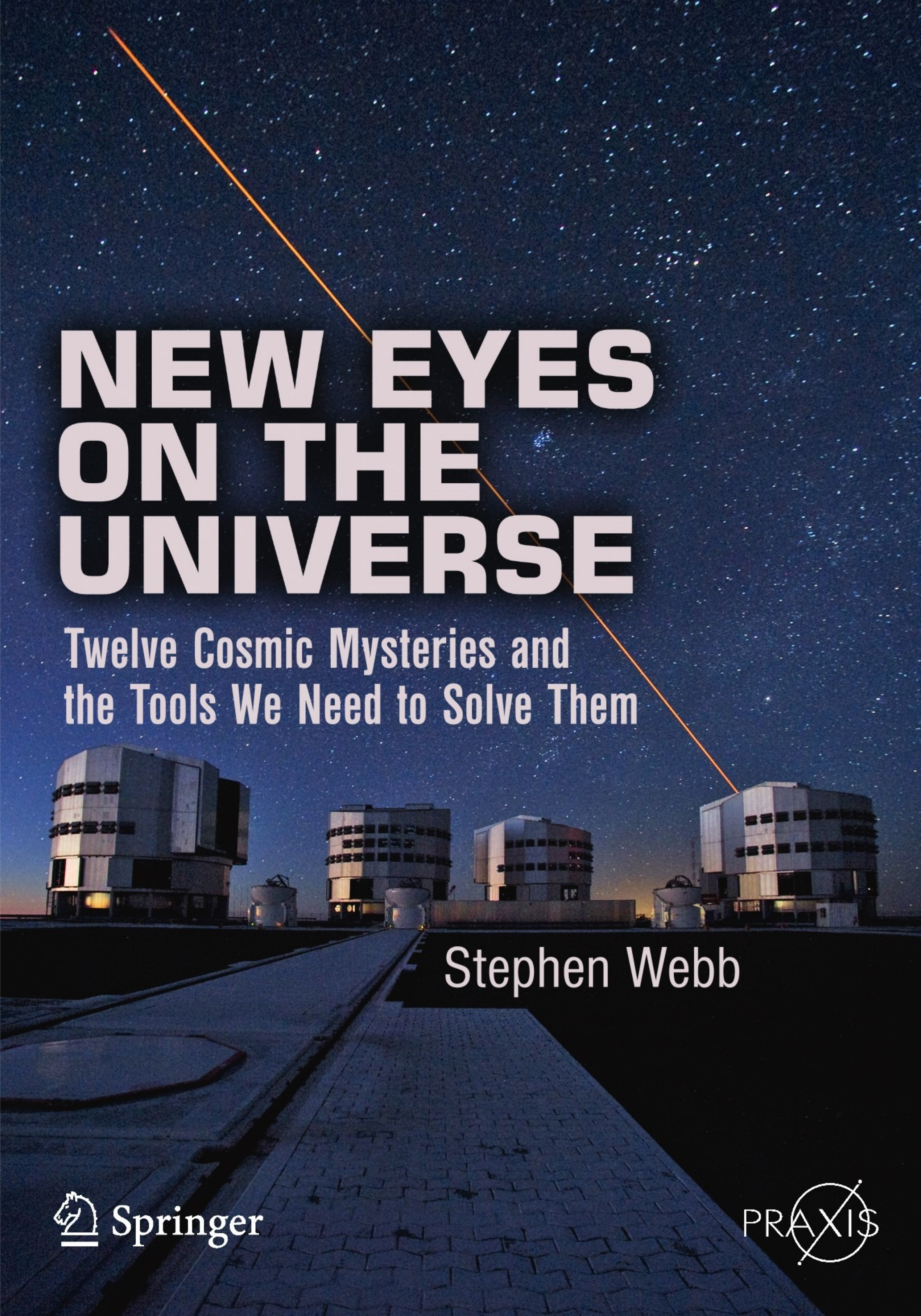

NEW EYES ON THE UNIVERSE

Twelve Cosmic Mysteries and the Tools We Need to Solve Them

Stephen Webb

Springer

PRAXIS

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To my brother, Peter

Contents

Preface

These are amazing structures: thousands of optical sensors deployed on kilometer-long strings, distributed throughout a volume that dwarfs the largest office block and interred deep in Antarctic ice; a gigantic tank of liquid argon, surrounded by ancient Roman lead and state-of-the-art photodetectors, sitting at the bottom of one of the world's deepest mines; a host of giant antennae placed on an almost inaccessible mountain top; a group of cables, each about the length of the Empire State Building and containing hundreds of photomultipliers encased in glass spheres, anchored to the Mediterranean seabed by underwater robots; and satellites – lots of them – orbiting Earth while they stare, unblinking, out into space. These constructions are cathedrals of science, all of them examples of a new type of astronomical telescope.

For a couple of years as a schoolkid I was obsessively interested in two things: telescopes and cricket. I joined the local amateur astronomy society, which gave me the chance to observe with a half-decent instrument. On those occasions when the telescope's availability coincided with a cloud-free sky (unfortunately, being in England, these were almost non-intersecting sets of events) I marvelled at the sights such an instrument afforded. And each time was the thought: "If I can see all this using a mirror that's the width of a cricket wicket, what could I see with a mirror that's the width of a cricket pitch?" (For US readers, a cricket pitch is 10 feet, or 3.05 m, wide.)

Later, when I began to study physics at university, I learned that professional astronomers already had access to a telescope bigger than the width of a cricket pitch: the 5 m Hale telescope at Palomar had been completed decades earlier. The view through Hale was indeed impressive: astronomers had already used it to study distant galaxies, to get glimpses of enormously energetic objects, and to firm up the notion of an expanding Universe. But

I learned that the view through even the world's largest telescope was never really sharp enough. In studying physics I was learning about a subject in which experiments could test theory to eight decimal places. Cosmology, on the other hand, seemed hopelessly imprecise. Basic parameters were quite uncertain, with cosmologists bickering over whether the Universe was ten billion years old or twenty. The telescopes of my boyhood imagination, it turned out, simply weren't powerful enough to do the job required.

And then it changed. About two decades ago astronomy and cosmology entered a Golden Age. Space-based telescopes such as Hubble and COBE transformed the field. Cosmology became a precision science. This Golden Age continues, and it's going to get even more glittering over the next few years: a plethora of giant telescopes – some of them in space; some of them hidden deep beneath ice, sea or rock; most of them bearing no resemblance at all to the traditional optical telescope – will soon start to observe. These marvels of technology will give humankind new eyes through which to study the Universe. And there's much to study. One of the lessons from the Golden Age is that the Universe is much stranger than previously thought. Mysteries abound: what's causing the Universe to blow itself apart? Why can't we see most of the matter in the Universe? Where *is* everybody?

This book is an introduction to a dozen of the most interesting mysteries over which astronomers are puzzling – and it's a guide, too, to the powerful new telescopes that will help solve those mysteries. Since the subject matter is so fast-moving, it's inevitable that there'll be interesting developments even as the book is being printed. For the latest on these questions please visit my website, stephenwebb.info, where I'll post regular updates.

* * *

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Finally, I would like to thank Heike and Jessica for showing so much patience with me over recent months. I would never have been able to finish this book without them.

1

Introduction

What is causing the Universe to blow itself apart? How come most of the matter in the Universe is invisible? Why haven't we heard from extraterrestrial intelligences? Astronomers are trying to answer these difficult questions – and solve many other cosmic mysteries – by building bigger and better telescopes. Not just telescopes that capture visible light, but telescopes that capture light from all parts of the spectrum – from radio waves all the way up to gamma-rays. By analyzing that radiation, astronomers can deduce vast amounts of information. In recent years astronomers have even begun to study the Universe in ways that don't depend on light at all. The result of all this activity is that, for the first time, we have a good understanding of the history and eventual fate of the Universe. And one by one those cosmic mysteries are starting to be solved...

Eyes on the Universe – New windows, new views – Let there be light – Barcoding the Universe – Telescopes for more than light – The Universe: a potted history

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Throughout most of history and prehistory our view of the heavens has been limited by the capacity of our eyes. The Sun dominates the daytime sky, of course, but when darkness falls people have surely always marvelled at the beauty of the Moon, puzzled over how five planets seem to wander across the celestial sphere, and wondered about the nature of the constant stars that stud the night sky. The rare appearance of a bright comet or the even rarer appearance of a nova heralded a brief period when the sky contained something out of the ordinary. For the most part, however, our Neanderthal and Denisovan cousins would have enjoyed much the same view that the Greeks or the Romans or the Mongol hordes enjoyed much later. For millennia, humankind's view of the sky was unchanging. And then came the telescope.

Eyes on the Universe

No one knows for certain when or where the telescope was invented, nor who invented it. The magnifying glass has been around for a long time and by the end of the Crusades people were making spectacles, so it's likely that many individuals at various times, when playing around with lenses, found that by holding a convex lens (one that causes light rays to converge) in front of a concave lens (one that causes rays to diverge) they had a simple device for seeing at a distance: faraway objects appeared closer and bigger. Place the convex **objective** lens and the concave eyepiece in a tube, about an arm's length apart, and you have a simple refractor – a telescope that works by bending, or refracting, the paths of light rays. Various refractors were developed in the late sixteenth century and the list of supposed inventors of the telescope is a long one. What's known for certain is that in 1608 Johannes Lippershey, a spectacle maker in the Dutch coastal town of Middelburg, became the first to both demonstrate a working model of a refracting telescope and apply for a patent. It makes sense then to call Lippershey the inventor of the telescope and 1608 the year of invention.

News of the invention spread quickly. Soon after Lippershey's patent application, Galileo Galilei built an instrument that magnified distant objects by a factor of three; a few weeks later and he had a telescope that magnified objects by a factor of eight; a few months later and he had a refractor that magnified by a factor of 30. And with that instrument he saw things no one else had ever seen. He saw the details of lunar craters and the phases of Venus. He saw the four largest satellites of Jupiter and objects that we now know were the rings of Saturn. He saw spots on the surface of the Sun. Galileo transformed humankind's understanding of the Universe.

It was Isaac Newton, surely the greatest of all scientists, who made the next major advances in optics. Newton passed sunlight through a prism and showed that a spectrum forms: white light splits into a rainbow of different colors – red through to violet. This was a crucial finding for several reasons, some of which we'll discuss later in this chapter. Purely in terms of telescope design Newton's discovery was important because it prompted a solution to what seemed a fundamental problem with refracting telescopes: the objective lens bends different colors by different amounts, thus limiting the sharpness of the image formed. It's a problem called chromatic aberration. Well, Newton showed experimentally that the reflection of light by a mirror was not subject to chromatic aberration and, with his characteristic single-mindedness, he set about constructing a reflecting telescope. Newton's design was unique: a curved main objective mirror brought light to a focus and then a diagonal secondary mirror, placed near the focus, reflected the image through a right angle into an eyepiece mounted on the side of the telescope. With the very first telescope of this design he repeated Galileo's observations. His second telescope, which he presented to the Royal Society in 1672, exceeded the power of Galileo's instruments and magnified objects by a factor of 38.

One of the functions of a telescope is of course to magnify *small* objects, which is why I mentioned the magnifying power of those early refractors and reflectors, but far more important for astronomers is a telescope's capacity for gathering light from *faint* objects and thus its ability to image objects that are otherwise too dim to see. Now, the light-gathering capacity of a telescope is related to the diameter of its objective lens or mirror: just as a larger bucket can catch more falling raindrops than a smaller bucket, so a larger objective can catch more light than a smaller objective. A larger objective also has the advantage of being able to resolve more fine detail than a smaller objective. So, all things being equal, bigger is better when it comes to telescopes. (As we'll see in later chapters, a smaller telescope can sometimes outperform a larger instrument. For example, the location of a telescope plays an important role in its effectiveness. Nevertheless, as a rule of thumb, a larger aperture is better than a smaller one.) Thus it was that a sort of astronomical 'arms race' took place in the eighteenth, nineteenth and twentieth centuries, with observatories around the world building ever-larger refracting and reflecting telescopes.

The limit for refracting telescopes was reached in 1897, with the construction of an instrument at the **Yerkes Observatory**; the Yerkes refractor had an objective lens that was 1.016 m in diameter. It's probably impossible to make a refractor with a lens much bigger than this because the lens must be held in place around its edge: gravity causes the center of the lens to sag and its images are inevitably distorted. The situation is better with a reflector since the mirror can be supported all over its surface. In 1917, the **Mount Wilson Observatory** opened the Hooker telescope, which had a mirror with a diameter of 2.5 m (the old measurement of 100 inches somehow sounds more evocative). Three decades later and the **Mount Palomar Observatory** opened the huge Hale telescope, which had a mirror with a diameter of 5.08 m. Modern giant telescopes are twice as large again. See figure 1.1.

Astronomers devoted decades of their working lives to these construction projects, not to get their names into the record books but so they could peer further and deeper into the Universe. They used these telescopes to discover more planets in our Solar System; to understand the place of the Solar System in the Galaxy; and to learn that there are hundreds of billions of galaxies in the Universe. In just four hundred years of telescopic observation, astronomers replaced a cosmological model in which Sun, Moon and planets revolved around Earth to one in which the Solar System is just an insignificant part of a much larger Universe. It was quite a change.

The optical telescope may have transformed humankind's view of Earth's importance, but other types of telescope have become even more important than refractors and reflectors in the ongoing quest to understand the Universe and our place in it. The key to the development of these new types of telescope lay in Newton's discovery that he could split sunlight into a spectrum of colors – it opened up completely new windows on the Universe.

Figure 1.1 *Telescopes have increased in sophistication and become much bigger over time. (a) Newton's 1672 reflector, of which this is a replica, had a diameter of 33 mm. (b) The Hale telescope, completed in 1948, is just over 5 m in diameter. (c) The ESO Very Large Telescope, based in Paranal, Chile, has four 8.2 m telescopes that can be linked to form an interferometer. The particular telescope shown here is called Antu. (d) An artist's impression of the TMT as it will look on Mauna Kea. This telescope, when it is completed in about 2018, will have a diameter of 30 m. ((a) Andrew Dunn; (b) Commons; (c) ESO; (d) TMT Observatory Corporation)*


(a)
(b)
(c)
(d)

New windows, new views

William Herschel constructed some of the best telescopes of his day, including the first 'giant' reflector – an instrument built in 1789 that had a 1.24 m mirror. He used those telescopes quite brilliantly. For example, even with one of his smaller telescopes he was able to discover Uranus, which was the first new planet found since ancient times. Herschel also found something that led eventually to a completely new kind of telescope.

In 1800, Herschel was engaged in a program of observing the Sun through different colored filters and, in making these observations, he came to suspect that different colors passed different levels of heat. To investigate this he passed sunlight through a glass prism – just as Newton had done more than a century earlier – and created a spectrum. He then used a thermometer to measure the temperature of each color of the spectrum, and compared the result with two identical thermometers that he placed well away from the spectrum. He measured the temperature of each color of the rainbow – violet, indigo, blue, green, yellow, orange, red – and in each case the recorded temperature was higher than the temperatures on the control thermometers. Furthermore, he found that different colored filters did indeed pass different amounts of heat: temperatures increased steadily from violet through to red. He decided, perhaps in a moment of idle curiosity, to measure the temperature just below the red part of the spectrum, a place where there was no visible sunlight. Rather than measuring the same temperature as the control thermometers, he found that the region below the red end of the spectrum had a temperature higher than any of the colors.

Herschel, being the thorough scientist that he was, experimented further on this invisible radiation beyond the red part of the spectrum. Apart from the fact that he couldn't see it, this radiation behaved in exactly the same way as visible light: it was transmitted, absorbed, reflected and refracted just like light. Herschel had discovered what eventually became known as **infrared** radiation (the prefix 'infra' meaning 'below', since the radiation lies below the red part of the spectrum).

The field of infrared astronomy was not long in arriving. In 1856, the astronomer Charles Piazzi Smyth combined his honeymoon with a scientific voyage to the mountain peaks of Tenerife. I'm not sure what his new wife thought of his activities, but Smyth began the modern practice of putting telescopes at high altitudes in order to observe under optimum conditions. Whilst on the peak of Guajara he used a **thermocouple** – a device that converts heat into electric current – to measure infrared radiation from the full Moon. Smyth's instrument didn't make an image in the way that optical telescopes usually do; the development of an infrared telescope had to wait. Nevertheless, his instrument enabled him to gain useful information about a celestial object – information that a 'normal' telescope could not provide. Smyth thus showed that it was possible to study the cosmos using something other than our aided or unaided eyes.

Soon after Herschel's discovery of infrared radiation, scientists demonstrated the existence of radiation beyond the blue part of the spectrum. What prompted the discovery in this case was the observation that certain substances, such as paper soaked in silver chloride, would darken when exposed to sunlight. Well, in 1801 a pharmacist by the name of Johann Wilhelm Ritter found that the violet end of the spectrum was more effective than the red end at darkening silver chloride paper – and that invisible radiation beyond the violet end of the spectrum was more effective still. Ritter had discovered what eventually became known as **ultraviolet** radiation (the prefix 'ultra' meaning 'beyond', since the radiation lies beyond the violet part of the spectrum). Newton's spectrum was thus richer than he could have known: radiation extended past both edges of the visible spectrum, into the infrared at one end and the ultraviolet at the other.

The full explanation of these various radiations came two hundred years after Newton's work, when in the 1860s James Clerk Maxwell showed that visible light, infrared and ultraviolet are all manifestations of the same thing. Maxwell argued that a changing electric field, generated for example by an oscillating electric charge, creates a changing magnetic field in a direction perpendicular to the original electric field; and a changing magnetic field creates a changing electric field in a direction perpendicular to the original magnetic field. See figure 1.2. This is therefore a self-propagating phenomenon: changing electric and magnetic fields generate each other – and move outward as a wave in a direction perpendicular to both of the fields. Furthermore, the wave moves through a vacuum with a particular speed – a speed that Maxwell calculated to be the speed of light. Visible light, infrared and ultraviolet are all examples of an **electromagnetic wave**.

Electromagnetic waves can be described and classified in the same way as any other type of wave. For example, any wave has a **wavelength**. Just as the wavelength of an ocean wave can be defined as the distance between successive crests or successive troughs, so the wavelength of an electromagnetic wave can be defined as the distance between successive crests or successive

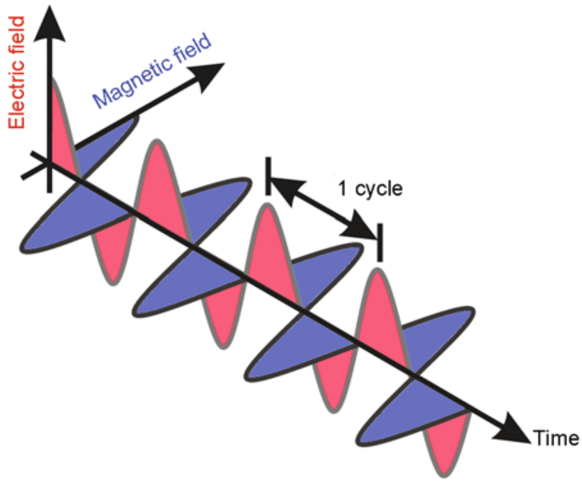

__Figure 1.2__ An electromagnetic wave consists of oscillating electric fields (red) and magnetic fields (blue). The electric and magnetic fields are perpendicular to each other; the direction of propagation of the wave is perpendicular to both. The wavelength is the distance between successive crests or successive troughs. The wave moves with the speed of light.

troughs of the electric (or magnetic) field. The difference in wavelength distinguishes the different colors of light and distinguishes visible light from infrared or ultraviolet light. The electromagnetic radiation that our eyes can detect has a wavelength between about 400 nm (violet light) to about 700 nm (red light). (One nanometer, or 1 nm, is one billionth of a meter. To give some indication of size, 1 nm is roughly the radius of the DNA helix.) Infrared radiation possesses a wavelength that's longer than 700 nm and ultraviolet radiation has a wavelength that's shorter than 400 nm, but neither type of radiation is different to visible light in a fundamental way. The reason we think of them as being different phenomena is because of a quirk of biology: evolution happened to provide us with optical sense organs that are sensitive to radiation in the 400–700 nm region. The fact that we don't directly see other electromagnetic wavelengths doesn't make those wavelengths somehow less important; it does mean, however, that we need instruments if we wish to observe them. (Some creatures are sensitive to other wavelengths. Bees, for example, are attracted by the ultraviolet properties of plants. The colors of flowers, which seem so beautiful to human eyes, may be entirely incidental: the main requirement of a flower is how it looks to bees in the ultraviolet rather than to humans in the visible.)

Another way of describing a wave is to use **frequency**. The frequency of a wave, whether ocean wave or electromagnetic wave, is simply the number of crests or troughs that pass by a given point every second. If one wave crest passes a given point every second then its frequency is one hertz (1 Hz).

Electromagnetic waves in the optical region have rather large frequencies when written in terms of hertz: violet light has a frequency of about 750 trillion hertz (7.5×10^{14} Hz) while that of red light is about 4×10^{14} Hz. A simple relationship exists between wavelength and frequency: multiply the two numbers together and you get the wave speed. For any electromagnetic wave, if you multiply its frequency and wavelength you get the speed of light. The speed of light is a universal constant so it follows that frequency and wavelength are inversely proportional: a longer wavelength means a lower frequency while a shorter wavelength means a higher frequency. Thus red light, with its relatively long wavelength, has a lower frequency than the shorter wavelength violet light.

Maxwell's work prompted an obvious thought: just as infrared and ultraviolet radiation extend beyond the ends of the visible spectrum, perhaps radiation exists with a wavelength longer than infrared or shorter than ultraviolet. We now know that the electromagnetic spectrum does indeed span a vast range: wavelengths can be longer than the distance from Earth to Moon or shorter than the diameter of an atomic nucleus. The part of the electromagnetic spectrum to which our eyes are sensitive is a minuscule fraction of the whole. See figure 1.3.

Although there is no *fundamental* difference between long-wavelength/low-frequency electromagnetic radiation and short-wavelength/high-frequency radiation – it's all just oscillating electric and magnetic fields – it turns out that radiation in different parts of the spectrum interacts with matter in quite different ways. This fact means it does make sense to distinguish between different types of radiation. Thus infrared radiation has a wavelength in the range between about 750 nm up to 1 mm. (Even within the infrared part of the spectrum there are subregions – far, mid and near – just as the visible part of the spectrum is subdivided into different colors). Radiation possessing a longer wavelength – between say 1 mm up to a few tens of centimeters – lies in the **microwave** region. Radiation with an even longer wavelength is in the **radio** part of the spectrum. The ultraviolet part of the spectrum possesses a range of wavelengths between about 400 nm down to 10 nm (and, as with the infrared and visible parts of the spectrum, the ultraviolet is divided into subregions: near, middle, far and extreme). If the wavelength is shorter than 10 nm then it's in the **X-ray** part of the spectrum; wavelengths shorter than about 0.01 nm belong to the **gamma-ray** region. All these wavelengths, from radio all the way up to gamma-rays, contain a trove of information for astronomers – if they can detect them.

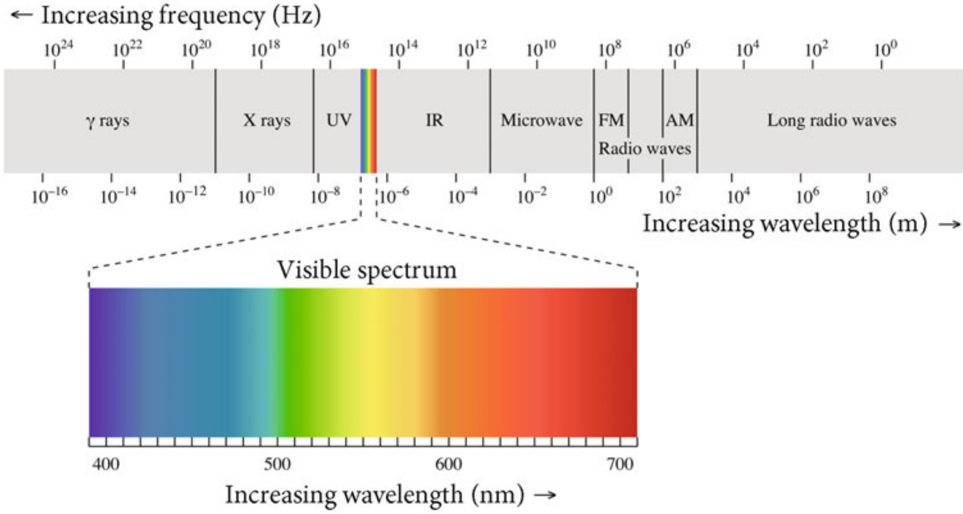

Figure 1.3 *The electromagnetic spectrum spans a vast range of frequencies. Compare the situation with a piano: each octave on the keyboard represents a doubling of frequency, which means that the frequency increases greatly in just a few octaves. A modern piano has a range of just over seven octaves. The human ear, for comparison, has a range of nine octaves. The electromagnetic spectrum has a range of 50 octaves! Take note of the small width of the optical frequencies compared to the overall spectrum; visible light is a tiny part of the spectrum.*

It didn't take physicists long to demonstrate experimentally the existence of these other regions of the electromagnetic spectrum. On the long-wavelength side of the infrared, Heinrich Hertz in 1886 showed how to generate and detect radio waves. On the short-wavelength side of the ultraviolet, Wilhelm Röntgen in 1895 systematically studied X-rays and in 1900 Paul Villard discovered gamma radiation. As the twentieth century dawned, physicists were investigating all parts of the electromagnetic spectrum, from radio waves (long wavelength/ low frequency) all the way up to gamma-rays (short wavelength/high frequency). Using the full spectrum for astronomy, though, turned out to be a difficult task.

Although Smyth was quick to make astronomical observations in the infrared, astronomers soon found that observations in the rest of the spectrum almost always encountered a problem: the atmosphere. Earth's atmosphere is effectively transparent to electromagnetic radiation in the visible part of the spectrum – which is, of course, why optical telescopes are useful for astronomy. The atmosphere is also transparent to many radio wavelengths, a few ultraviolet wavelengths (as you yourself can testify if you've ever been sunburned) and a some infrared wavelengths (although in general you have to go high in a balloon or, as Smyth did, climb a mountain to detect these wavelengths). But the atmosphere blocks most wavelengths quite effectively. It presents a barrier to astronomy throughout most of the electromagnetic spectrum.

Since the atmosphere is transparent at many long wavelengths, radio and some microwave astronomy can take place with ground-based instruments. Thus radio astronomy has a relatively long history. It can be said to date back to 1931, when Karl Jansky discovered that the Milky Way was a source of radio emission; six years later, Grote Reber had built the first dedicated radio telescope. However, astronomy at the shorter wavelengths – ultraviolet, X-ray and gamma-ray astronomy – could not start in earnest until the development of reliable satellite technology. It was only in the 1960s, then, that astronomers could put their instruments above the blanketing effect of Earth's atmosphere and observe at all wavelengths.

With the latest generation of telescopes astronomers are studying the Universe through the radio, microwave, infrared, optical, ultraviolet, X-ray and gamma-ray windows. It's a multi-wavelength view and, as we shall learn, the vista is stunning. The change in worldview brought about by being able to observe throughout the spectrum is almost as large as that wrought by Galileo's first telescopes.

Let there be light

Astronomy at the shorter wavelengths tells us we live in a Universe that's home to violent explosions and collisions, to processes involving incredible temperatures and vast releases of energy. Astronomy at the longer wavelengths enables us to understand the way in which cosmic structures – and even the Universe itself – came into being. But how can astronomers deduce all this information just from studying electromagnetic waves?

In order to squeeze as much information as possible from light, astronomers need to understand how electromagnetic waves are created. With that understanding comes the ability to use telescopes to discover not just objects too faint to see with the naked eye, but also to learn how hot those objects are, what they are made of, their surface gravity, how fast they are moving… Galileo could never have dreamed of how much information a telescope can give.

The rough-and-ready explanation of how electromagnetic waves come into being is that matter generates them. In particular, the waves are created by the atoms of which matter is composed.

An atom consists of one or more negatively charged **electrons** swarming around a central massive nucleus, which in turn consists of one or more positively charged **protons** and zero or more electrically neutral **neutrons**. In any atom, the number of protons is the same as the number of electrons so that the atom overall is electrically neutral. Since the electrons are orbiting the nucleus, those negative electrical charges are constantly being accelerated. One's first thought is likely to be that these electrons are the source of electromagnetic waves: Maxwell's theory says that accelerating electrons emit electromagnetic radiation. However, if the atomic electrons radiated they would lose energy, and thus they would spiral almost immediately into the nucleus. Clearly this doesn't happen: atoms are stable enough to form matter. In fact, it turns out that atomic electrons occupy only certain orbits – those orbits, or energy levels, allowed by quantum mechanics – and a basic principle of quantum mechanics is that electrons occupying allowed orbits do not radiate energy. But if atoms don't radiate because of orbiting electrons, how do they generate electromagnetic waves?

Matter can generate electromagnetic waves in several different ways. For example, **synchrotron radiation** is generated whenever the paths of fast-moving charged particles are bent by a magnetic field; such a situation occurs when the intense gravitational field close to a black hole whips matter around its event horizon, or when cosmic rays encounter magnetic fields. Quite different mechanisms for producing electromagnetic radiation arise in certain events that take place at the atomic and nuclear level; we shall discuss these in more detail in the next section. However, perhaps the most important way in which matter generates electromagnetic waves occurs simply because matter is hot.

If we heat a body it will radiate. We all know that. We talk, for example, about things being 'red hot' or 'white hot' – objects that are radiating visible light simply because they are at a high temperature. The mechanism behind the radiation, roughly speaking, is that heat causes the atoms and molecules in a solid to vibrate. Some electrons become detached from individual atoms and are then able to move freely throughout the solid. The distributions of electrical charges are then complicated to describe, but in essence it's the vibration of these charge distributions, rather than the oscillations of orbiting electrons, that generates electromagnetic radiation.

Physicists long sought to describe this radiation in a quantitative fashion and they realized that in order to predict how a body will *emit* radiation it pays to understand how radiation is *absorbed*. Well, absorption depends on the body in question. If you're talking about glass then most of the light seems to go right through without being absorbed. If you're talking about a shiny, metallic surface then much of the light falling on it gets reflected without being absorbed. But if you're talking about a material such as the black vinyl seats you might find inside a car, then you find that such material readily absorbs light and becomes warm. (I can personally attest to this, having once jumped into my car wearing only shorts. The car had been parked in direct sunlight. I jumped out quicker than I jumped in.) What accounts for these differences?

In the case of glass – again, roughly speaking – the structure of the material is such that the charge distributions are only able to oscillate at certain frequencies. Since none of those frequencies happen to correspond to the frequencies of visible light, a light wave passing through the glass loses no energy because it can't get those charges to oscillate. Glass is thus transparent to visible light (which is why we use it for windows, as if that needed spelling out). Note that the situation is different at different frequencies: glass can be opaque in the ultraviolet and in the infrared, where the frequencies involved are such that the charges *can* oscillate. In the case of a shiny metal surface, it turns out that any light waves falling on it force the free electrons into large oscillations and those oscillating electrons emit electromagnetic radiation – the light is reflected, in other words. In the case of light waves falling on a dark surface it turns out that the electric field can drive the electrons into motion (unlike in glass) but the process is not particularly effective (unlike in metal). Any unattached electrons that are driven into motion quickly collide with atoms, and they transfer their kinetic energy into heat. Thus a dark surface absorbs the light wave with very little reflection, and energy is transformed from the light wave into heating up the object.

Now, a good absorber of radiation is a good emitter of radiation. Again, the reason for this is to do with the distribution of free charges in the material. The electrons inside a black object such as coal bounce around and each time they collide with something they are accelerated and emit radiation. Coal is a good emitter. The electrons in a metal, however, move around more freely before colliding and undergoing acceleration; metals are therefore less efficient than dark objects at emitting radiation. The charges in glass are tied down tightly, so glass is a poor emitter. In fact, at any given temperature and frequency a body emits radiation exactly as well as it absorbs radiation. That's why an understanding of how radiation is absorbed allows one to understand how radiation is emitted.

It follows from the above discussion that if we want to know precisely how a body will radiate then we need to understand its detailed structure. Well, that's a difficult problem so physicists did what they always do in such situations: they invented a simplified, idealized situation that they *could* analyze, and then compared that model with the real world in the hope of learning something. Thus it was that the physicist Gustav Kirchhoff introduced the idea of a **blackbody** – a perfect absorber (and hence 'black' at room temperatures) and a perfect radiator – in order to learn more about radiation.

Kirchhoff and his colleagues soon took up the challenge of measuring the amount of energy emitted from a blackbody at different wavelengths as its temperature changes. They learned several interesting things. First, they found that the energy spectrum of blackbody radiation has a quite specific shape. A blackbody emits radiation of all wavelengths, so the blackbody or thermal spectrum is continuous, but there's always a wavelength at which the radiated energy is a maximum. (Synchrotron radiation also has a continuous spectrum, but it has a very different shape to a blackbody spectrum.) Second, the characteristic shape and the location of the peak wavelength depend *solely* upon the temperature of the blackbody. It doesn't matter what the body consists of, or how big it is, or any other complicating factor: every blackbody behaves in precisely the same way. Third, as the temperature rises the peak wavelength moves to shorter wavelengths/higher frequencies. (We know this from everyday life – a red-hot poker becomes orange and then yellow as it gets hotter.) Fourth, as the temperature increases, the height of the peak becomes very much higher. (Again, we know this from everyday life: an object becomes *very* much brighter as it gets hotter.) See figure 1.4.

There's no such thing as a perfect blackbody but it turns out that many celestial objects produce excellent blackbody spectra. Moons, planets and stars emit electromagnetic radiation simply because they are hot, and this is the way that much of the electromagnetic radiation in the Universe, and much of the radiation picked up by our telescopes, is generated. If an object is really cold then it will be dim and will radiate mainly in the radio or microwave regions. A cool object – such as you, gentle reader – radiates mainly in the infrared region. A hot object, such as a star, with a temperature measured in thousands of degrees, will emit significant amounts of infrared and ultraviolet radiation but its radiation will peak in the visible region –

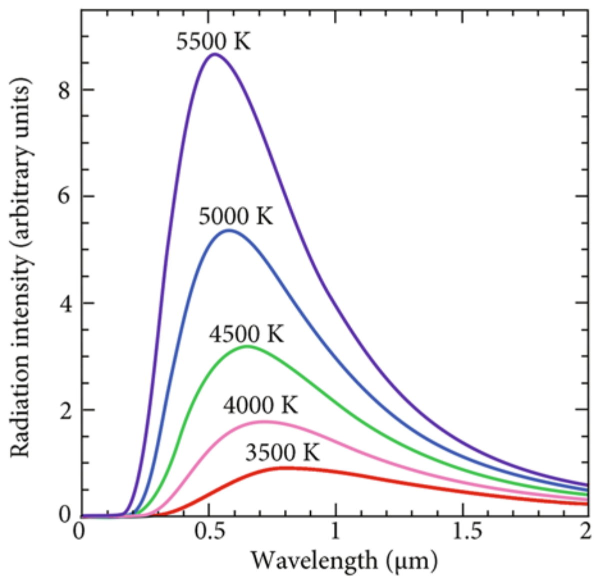

Figure 1.4 *Blackbody emission depends on the body's temperature, but not on factors such as the body's chemical composition or shape. At higher temperatures, the radiation peak moves to shorter wavelengths. At 3500 K the peak is at 0.83 μm; at 5500 K the peak shifts to 0.53 μm.*

and the hotter the star, the brighter and bluer it is. The radiation peak of an extremely hot object such as an intergalactic gas cloud, with a temperature measured in the hundreds of thousands or even millions of degrees, is in the ultraviolet or even the X-ray region. (As we'll see, the even shorter-wavelength gamma-rays are created in other, highly energetic, processes.)

With appropriate telescopes, then, electromagnetic radiation of all wavelengths can be detected – and by locating the peak of the radiation astronomers immediately know the temperature of the object that generated the radiation. That's important information.

But much more than a knowledge of an object's temperature can be gleaned from a study of electromagnetic radiation.

Barcoding the Universe

The radiation coming from a blackbody contains every wavelength, even if most of the wavelengths occur in minuscule amounts. There are no gaps in a thermal spectrum. Look closely at the solar spectrum, however, and you

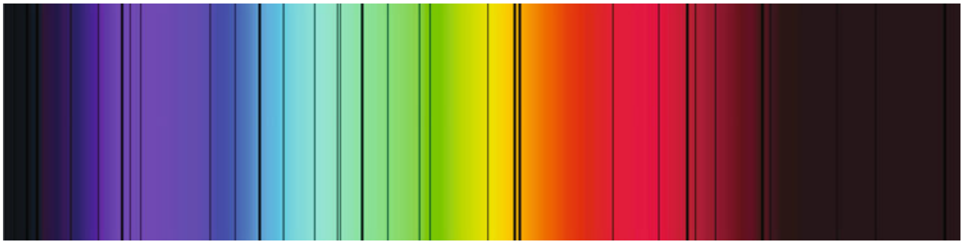

Figure 1.5 *This absorption spectrum shows some of the absorption lines seen in the Sun's spectrum.*

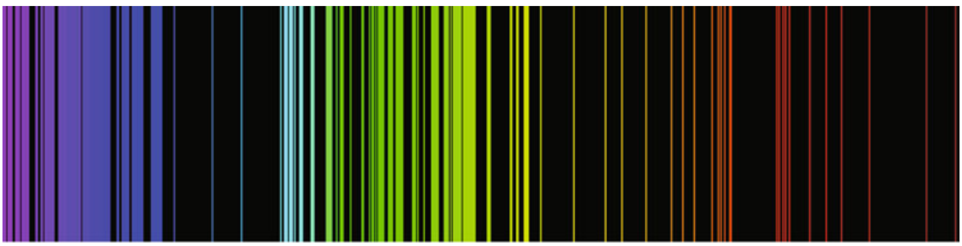

Figure 1.6 *This emission spectrum shows some of the emission lines of iron. By identifying the characteristic lines in an object's spectrum, astronomers can determine the presence of chemical elements in that object.*

see lots of dark lines superimposed on the continuous spectrum – wavelengths where the energy has been absorbed by relatively cool gas in the Sun's outer layers. Such lines are called, naturally enough, **absorption lines**. See figure 1.5. A hot, low-density gas cloud (which is a collection of widely separated atoms, and is thus nothing like a blackbody) will have a discrete spectrum, a series of bright lines called **emission lines**. See figure 1.6. What's going on in these cases?

Well, as already mentioned, the electrons in any given atom occupy only certain well-defined orbits. Each orbit corresponds to a particular energy level. An electron occupying the orbit closest to the atomic nucleus has the lowest energy; the farther out from the nucleus, the more energy the electron possesses. When an electron moves from one level to another it must do so by either absorbing or emitting a particular quantum of energy, corresponding to the difference in energy between the two orbits. For any particular atom the differences between different energy levels are fixed and unchanging; for example, an electron jumping from the third allowed energy level in a hydrogen atom to the second allowed level will always emit *precisely* the

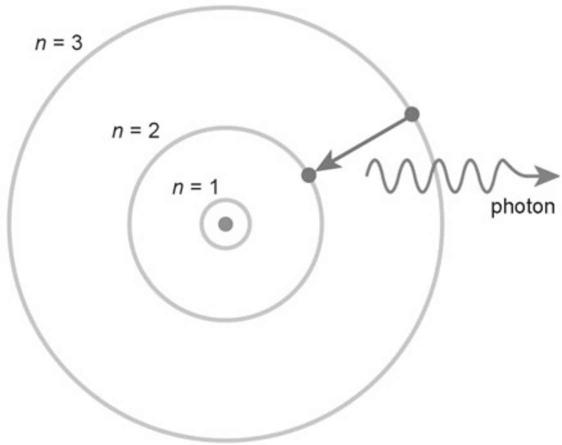

Figure 1.7 *The electrons in an atom exist only at certain energy levels. Different atoms possess different levels. The farther from the nucleus an electron is, the greater the energy it has. An electron in the third energy level (in other words n = 3) thus has more energy than an electron in the second energy level (n = 2). When an electron drops from a higher energy level to a lower energy level the excess energy is carried away by the emission of a photon – in other words, the atom emits radiation. Since particular energy levels are involved, the photon carries a quite specific energy: energy is quantized.*

same amount of energy. An emission line therefore occurs when an electron falls from a higher level to some lower level and radiation carries away the difference in energy. See figure 1.7. (An absorption line occurs when radiation possesses just the right energy to kick an electron from one level to another.) Thus emission in atomic processes is another way in which electromagnetic radiation is generated.

A couple of crucial points follow from this quantization of energy levels. The first is that the electromagnetic radiation generated in an atomic process is created at a particular position in space and a particular instant in time; similarly, absorption takes place at a localized point. This is behavior more typical of a particle than a wave. It's an example, of course, of the famous wave–particle duality of quantum mechanics. Electromagnetic radiation is a wave: as it propagates through space it moves as a wave, and can undergo phenomena typical of a wave such as diffraction, reflection and refraction in the same way as any other wave. But electromagnetic radiation is also a particle: when radiation is emitted or absorbed by matter it does so as a particle. The particle of electromagnetic radiation is called the **photon**.

The second crucial point is that photons carry energy in an amount that's directly related to the frequency of the radiation: the higher the frequency the greater the energy of the photon. So just as electromagnetic waves can be classified in terms of their frequency and wavelength, they can also be classified in terms of the energy they carry. Physicists usually measure the masses and energies of particles in terms of a unit called the **electronVolt**, which has the symbol eV. The energy of a radio photon is extremely small, so small that it makes little sense to dwell on its particle aspects; it almost always makes more sense to discuss radio waves in terms of wavelength and frequency. For wavelengths shorter than the microwave, however, it's as convenient to talk about photon energy as about wavelength or frequency. Photons of visible light carry energies between about 1.8 eV (red light) to about 3.4 eV (violet light). Ultraviolet photons carry energies between a few eV up to about 100 eV. X-ray photons carry energies in the range 100 eV up to 100 000 eV (or 100 keV). Gamma-rays are photons with energies greater than 100 keV. (Gamma-rays are usually generated in processes involving the atomic nucleus rather than atomic electrons; such processes generally take place at much higher energies.)

Now, since each atom can absorb or emit radiation only at certain wavelengths, a particular pattern of lines acts like the identifying barcode that manufacturers put on their products. Find a set of lines in an object's spectrum – either dark absorption lines in a continuous spectrum of a star, say, or bright emission lines in the spectrum of a gas cloud – and you can infer the presence of a particular chemical element. It doesn't matter how far away the object lies: if you can identify the lines then you can learn something about its chemical composition. To me, that's amazing!

The unique pattern of lines belonging to a particular element won't always show up in the same place in the spectrum. If the object is moving then the spectral lines will shift away from their usual position; this is the **Doppler effect**, which occurs with any wave phenomenon when motion is involved. (We've all heard the Doppler effect in the changing pitch of a siren as an emergency vehicle first moves towards you and then recedes.) Sometimes the spectral lines will be shifted towards the shorter (bluer) wavelengths; in other words, they'll be blueshifted. A blueshift denotes that the object is approaching. Sometimes the lines will be shifted towards the longer (redder) wavelengths; in other words, they'll be redshifted. A redshift denotes that the object is receding. Furthermore, the size of the observed shift tells you how fast the relative motion is: the faster the motion, the larger the shift.

It's clear, then, why the ability to capture electromagnetic radiation is so important to astronomers. By building bigger and better telescopes, and increasingly sensitive instruments with which to study spectra, astronomers can see objects that are too faint to see with the unaided eye; they can determine an object's temperature; they can investigate its chemical composition; they can tell whether it's moving away from us or towards us; they can ascertain the sizes of stars and the strengths of their magnetic fields; they can find out about the orbiting of planets around stars and accretion disks around black holes; there's a host of other information they can glean too. And they can do all this even if the object lies halfway across the Universe. By capturing electromagnetic radiation at the various wavelengths, astronomers learned how the Universe was born and how it is put together. The new generation of telescopes are going to provide even more detail.

In recent years, however, it has become increasingly clear that these instruments for studying electromagnetic radiation aren't the *only* tools in the astronomers' toolkit.

Telescopes for more than light

Almost all of humankind's current knowledge of the cosmos comes from information carried by electromagnetic waves. These waves are such important information carriers for several reasons: the Universe is awash with them; they are detectable over a vast range of wavelengths and thus provide information on many different types of source; they are stable and electrically neutral so they can travel for billions of light years until something – possibly a telescope – blocks their path; and they can contain detailed information on many aspects of the objects with which they have come into contact along the way. However, it's not only electromagnetic radiation that rains down on Earth. Other stuff reaches us from the depths of space. If it can be stopped and studied, if we can construct a 'telescope' with which to 'observe' it, then astronomers have yet another tool with which to learn something about the Universe. And those tools will complement the information provided by electromagnetic radiation: different messengers will deliver different sorts of information.

For example, if you have an instrument that can detect radioactivity then you'll soon notice that your instrument registers a certain level of radiation even in the absence of obvious radioactive sources: there's always some background radiation. This phenomenon puzzled the early investigators of