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Excerpt
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Introduction

Night vision – the ability of infrared light to penetrate dust and to light up the dusty universe – and also the new vision of the night sky, the universe that infrared astronomy has unveiled.

All astronomy starts from the night sky, the picture of the universe we see with our own eyes: the stars and constellations, the Milky Way. We have become used to the idea that there is a universe beyond the constellations, revealed by the giant telescopes of the astronomers. We can still imagine the *Hubble Space Telescope* to be a giant extension of our own eyes, and its images are still images made in visible light. Much harder to grasp is the universe that is revealed in invisible light, such as the infrared radiation that is the subject of this book. I've called the book *Night Vision* for two reasons. Firstly, infrared sensors and binoculars are already widely used to aid seeing in the dark, or night vision. And secondly, my goal is to try to make the infrared universe as familiar to you as the night sky, so that when you look out at the night sky you can also imagine what it would look like with infrared eyes, and therefore see the new vision of the night sky that the infrared gives us.

Above all, infrared astronomy is about the cool, dusty universe. Spread between the stars are tiny grains of dust, similar to sand and soot, and these absorb the light from stars and reradiate the energy as infrared radiation. There are dense clouds of gas and dust within which new stars are forming, and only with infrared light can we peer into them. Dying stars and massive black holes are often shrouded in dust, which shines in the infrared. And the cool bodies of the Solar System, planets, comets and asteroids are mainly radiating infrared light. In the infrared and submillimetre parts of the spectrum, we see galaxies in formation, undergoing violent bouts of star formation often caused by collisions between smaller fragments. And we see the cool glow left over by the hot fireball phase of the Big Bang itself.

NIGHT VISION

There are two subtle things about human night vision. Firstly, it takes about half an hour to get fully working, and we need to be away from any direct light. Initially, if we go outside at night from a lighted room, we blink and see very little of the stars. After a while, the eye adjusts and we start to see the fainter stars. And secondly, our night vision works better at the edge of our visual field than in the centre. To see the faintest stars and nebulae, we need to look 'out of the corner of our eye'.

Now these are consequences of the way the human eye works. There are two types of receptors in the eye, *rods* and *cones.* The cones are packed into the centre of the eye's detector, the retina, and are responsible for our main vision. They are sensitive to colour, and there are three distinct types of cone receptors, with sensitivity to red, green or blue light. By combining the information from these three types of cones, the brain is able to give us the full experience of colour, and we are able to discriminate more than one hundred different shades of colour. The far more numerous rods, by contrast, are dominant at the edge of the retina and are more sensitive to low levels of illumination, hence their importance for night vision. They do not have any colour discrimination, but they are very sensitive to movement, and so we catch sight of something moving behind us at the edge of our vision. It's as if the eye is really two visual systems in one, one for normal daytime vision and the other for night vision and for detecting movement.

If we go out into a dark night, then at first our vision is very insensitive. Within about five minutes we notice a dramatic improvement in sensitivity – by a factor of 50. This results from the cones at the centre of our vision becoming adapted to the dark. After about half an hour there is an even bigger improvement, by a further factor of 200, as the rods become adapted. In other words, from first entering the dark to full dark adaptation half an hour later, the sensitivity of our vision has improved by a factor of 10,000.

When our eyes have become 'dark adapted', on a clear night, away from the polluting light of towns and cities, we then have the wonderful display of the night sky: the sparkling stars with their different colours, red for Betelgeuse, the Armpit of the Giant, Orion; blue for Vega, the brightest star in Lyra; and white for Sirius, the Dog Star. We see star clusters such as the Pleiades, and the familiar constellations of Ursa Major, Cassiopeia and Orion that we can all recognize, which are delineated by bright stars that happen to lie together on the sky but can be at a wide range of distances. And we can pick out the wandering planets and the Moon, and the fuzzy stream of light across the sky, the Milky Way, which is the flattened distribution of hundreds of billions of stars of our own Galaxy, seen from the Solar System's location near the edge. All this looks even better if you can get to a mountaintop, as astronomers like to do. And then with our wonderful modern telescopes we open up a more distant landscape of billions of galaxies and reveal shoals of faint stars and hot gas clouds in our Milky Way Galaxy, often streaked with dark patches.

I want to try to convince you that this familiar night sky and the universe of visible galaxies beyond are only a small fraction of the cosmic world. About half of the light that reaches the Earth from the universe is invisible to the human eye and is infrared light. And the infrared cosmic landscape is almost unimaginably different from the night sky we see with the human eye or with optical telescopes. It has only been during the past 50 years that the veil on this cool, dark landscape has been drawn back. I've been lucky enough to know most of the pioneers of modern infrared astronomy and to participate in some of these great discoveries.

Across the various species, eyes appear to have evolved independently several times, and Simon Conway Morris, in his book *Life's Solution*, emphasizes how some of these different eyes, for example those of the octopus and humans, have converged to a rather similar design.[1] Especially interesting is the case of the rattlesnake, which has evolved a primitive infrared eye. This allows it to see in the dark, where its prey appears as a warm, glowing, bright infrared object (see Figure 1.1). So the rattlesnake really does have night vision. If humans had evolved this ability, I would not need to be writing this book. I shall try to bring to life, for infrared-blind humans, the invisible universe.

Because we do not have infrared vision, we have had to develop ways of detecting infrared radiation, and until recently this was a slow process. Today soldiers routinely have infrared binoculars to scan the night-time battlefield. Firefighters use infrared goggles to detect people in smoke-filled buildings. And wildlife programmes on television use infrared cameras to watch nocturnal animals such as foxes and badgers. Infrared binoculars were first developed for military use during the Korean War, but much of the routine infrared capability we now use, including our television remote control, has developed only in the past 20 years.

THE INVISIBLE WAVELENGTHS

Infrared radiation was first discovered by William Herschel in 1800. Isaac Newton (1642–1727) had shown that if the light from the Sun is passed through a prism, it becomes spread out into the colours of the rainbow, the *spectrum.* For mystical reasons, he chose to characterize this as seven colours: red, orange, yellow, green, blue, indigo and violet. In reality, the colours merge imperceptibly from one to another and there are an infinite number of possible colours. Herschel asked himself the question: what happens beyond the red and beyond the violet? By placing a mercury bulb thermometer beyond the red end of the spectrum and watching the mercury rise up the tube of the thermometer, he showed that the Sun is emitting radiation beyond the red end of the spectrum, infrared radiation. And he realized that this radiation, which he called 'invisible light', is the same thing as radiant heat. Now we do not 'see' radiant heat but we can feel it through our skin, so our skin is a detector of infrared radiation. You will certainly have noticed that when many people gather in a cold room or railway carriage, it soon warms up from the heat of the bodies present. The human body radiates about a hundred watts of infrared power, so our body's ability to sense infrared radiation is our third, crude eye.

Newton thought that light consisted of 'corpuscles', or discrete particles. Today we know this is partly true, although Newton had the completely wrong idea that these particles of light were emitted by the eye. Through the eighteenth century it began to be realized, by Robert Hooke (1635–1703), Christiaan Huygens (1629–1695), Leonhard Euler (1707–1783) and especially Thomas Young (1773–1829), that the best way to understand most of the known phenomena of light was to think of light as waves. The different colours then corresponded to different wavelengths of light. These waves are very short in length and have to be measured in terms of microns, a micron being a millionth of a metre, or a thousandth of a millimetre. To set the scale, a human hair is about 100 microns in diameter. Red light corresponds to light of wavelength 0.7 microns and violet light has wavelength 0.4 microns, so the visible spectrum of light spans the narrow range of wavelengths from 0.4 to 0.7 microns. What Herschel had shown was that there is radiation with a wavelength longer than 0.7 microns. Only a few years later, Johann Ritter (1776–1810) showed the existence of ultraviolet

Figure 1.1. The same scene viewed in visible and infrared light. In visible light the arm is concealed by the black polythene sack, but it can be seen clearly in infrared light.

radiation, light with a wavelength less than 0.4 microns, by showing that silver chloride was blackened by light from the Sun beyond the violet end of the spectrum.

The breakthrough in understanding came when the Scottish physicist James Clerk Maxwell (1831–1879) realized in 1864 that light consists of vibrations in a combined electric and magnetic field.[2] By uniting and extending the laws of electricity and magnetism that had been developed by Carl Friedrich Gauss (1777–1855), Michael Faraday (1791–1867) and André-Marie Ampere (1775–1836), Maxwell was able to show that there could be electromagnetic waves and that their speed would be exactly the same as the known speed of light. These waves could be characterized by their wavelengths, and the difference between the then known types of light, namely visible, infrared and ultraviolet, was simply one of wavelength. The wavelength is simply the distance between successive crests or successive troughs of the wave. The type of wave can also be characterized by the number of waves passing per second, or frequency. The product of the wavelength and frequency is then just the speed of light, which is the same for all types of light. At any point in space, an electric charge will be pushed in the direction of the local electric field, if there is one. A magnet will line itself up in the direction of the prevailing magnetic field. When a light wave passes, what really happens is a trembling of the electric and magnetic fields and then stillness again. That trembling is the light wave, so we now talk about the *electromagnetic spectrum* of radiation, meaning all the possible kinds of light or radiation. Starting at the shortest wavelengths, we have gamma rays, x-rays, ultraviolet, the visible range from violet to red, then infrared, submillimetre, microwave and radio. Maxwell's prediction of electromagnetic radiation of different wavelengths was confirmed by the discovery of radio waves by Heinrich Hertz (1857–1894) in 1887 and of x-rays by Wilhelm Roentgen (1845–1923) in 1895.

While Maxwell's theory brilliantly explained the known properties of light, the advent of quantum theory in the early twentieth century introduced another aspect of light. In 1905, Albert Einstein (1879–1955) showed that we have to think of light both as a wave and as a particle. The particle of light became known as the *photon*, and a photon carries a precise amount of energy, which is inversely proportional to the wavelength of the light. So x-ray photons have very high energy, whereas radio photons have low energy. From gamma rays to the longest-wavelength radio waves there is a factor of one thousand million million (10^{15}) increase in wavelength (Figure 1.2). The visible

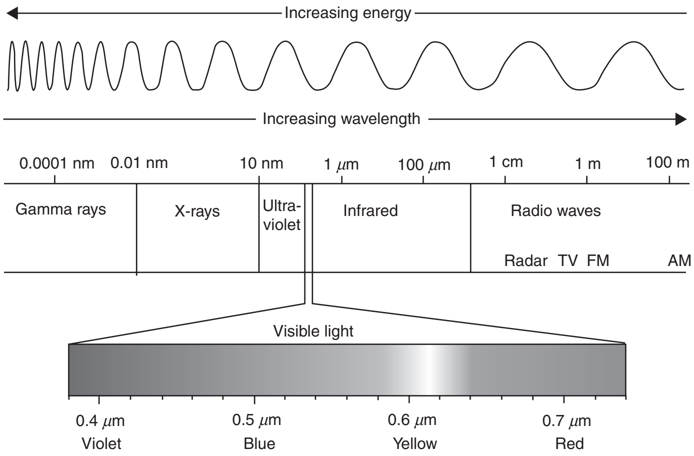

Figure 1.2. The electromagnetic spectrum, showing the gamma ray, x-ray, ultraviolet, visible, infrared and radio bands. The visible band stretches from wavelengths 0.4 to 0.7 microns, the infrared and submillimetre band from 0.7 to 1000 microns (1 millimetre).

band is just a factor two spread in wavelength, only one-fiftieth of the total. It's amazing what a world of colour we experience from this tiny range of wavelengths. But equally the universe of invisible wavelengths is unimaginably different from the familiar universe of the visible band.

The twentieth century saw the opening up of all these different wavebands for astronomy and the birth of the astronomy of the invisible wavelengths. Radio astronomy began quietly with an investigation of radio "static" interference at a wavelength of 15 metres by Karl Jansky (1905–1950) at Bell Telephone Laboratories in Holmdel, New Jersey, in 1930–3. He built a rotatable aerial array 30 metres long and 4 metres high, which was nicknamed the 'merry-go-round', mounted on four wheels taken from a Model T Ford (Figure 1.3). He found that part of the static was caused by thunderstorms, but there remained a steady hiss from a direction that moved around the sky a little each day. This direction turned out to be the constellation Sagittarius. Jansky had discovered radio emission from the Milky Way. This discovery had little media impact apart from a sardonic comment by *The New Yorker*: 'This is the longest distance anyone ever went looking for trouble'. Few professional astronomers took any notice of Jansky's results either, and the next step was taken by an American amateur astronomer, Grote Reber (1911–2002), who made detailed radio maps of the Milky Way between

1938 and 1944. Meanwhile, in wartime Britain, John Hey (1909–2000), investigating apparent enemy jamming of radar installations, discovered radio emission from the Sun. After the war, he went on to detect several discrete astronomical sources of radio waves and inspired the formation of radio astronomy groups at Cambridge and Jodrell Bank in Britain, and in Australia. The big breakthrough came with radio surveys of the sky made in the 1950s and 1960s, especially at Cambridge and in Australia. These led to the discovery of remarkable new types of objects, galaxies that were very powerful emitters of radio waves, called *radio galaxies*, and distant radio sources which looked like stars at optical wavelengths, which became known as quasi-stellar radio sources, or *quasars*. The latter were hundreds of times more luminous than the light from our whole Galaxy, yet their rapid variability, on timescales of years or months, meant that this huge output was coming from a region not much larger than the Solar System. Ultimately these regions were understood as massive black holes at the centres of galaxies. A *black hole* is formed when a massive body collapses under the influence of gravity into such a compressed state that light can no longer escape from it. The black holes responsible for quasars are typically a hundred million times more massive than the Sun. The 1960s saw the discovery of another exotic type of object, *pulsars*, radio sources that pulsate rapidly and are associated with rapidly spinning compact neutron stars. A *neutron star* is a dead star that has exhausted its nuclear fuel and become so compressed that its radius is only ten kilometres, smaller than Los Angeles or London.

While radio waves from the universe reach the ground, x-ray astronomy is only possible from space, because the Earth's atmosphere strongly absorbs x-rays. X-ray astronomy began in 1948 when American Thomas Burnight detected x-rays from the Sun by using a captured German V2 rocket. In 1962 Riccardo Giaconni discovered a compact x-ray source in the constellation of Scorpius while trying to observe the Moon with a rocket-borne x-ray detector. This was the first of many x-ray sources found that are associated with very compact dead stars. When a star reaches the end of its life, its core collapses to form a very small remnant: a star like the Sun ends up as a *white dwarf* star, a very hot object about the size of the Moon. More massive stars end up either as neutron stars or the ultimate compact object, a black hole. The x-ray emission comes from gas that falls onto the compact object or forms a disk of very hot gas orbiting it. The first x-ray survey of the sky was undertaken by NASA's *Uhuru* satellite in 1970, and there have been many subsequent x-ray missions of

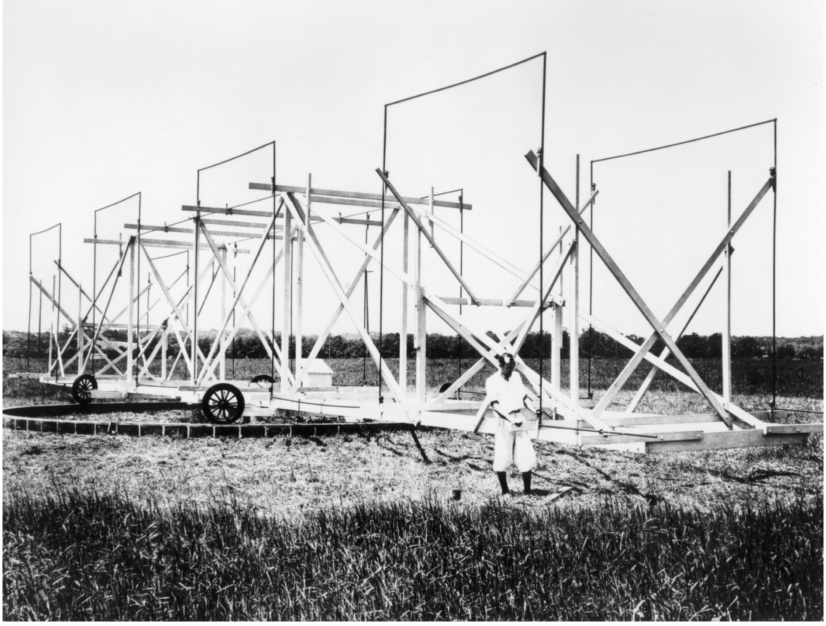

Figure 1.3. The ‘merry-go-round’ antenna with which Karl Jansky, pictured here, discovered radio emission from the Milky Way in 1930–3.

ever-increasing sophistication. *Uhuru* found dozens of compact x-ray sources, the first x-ray galaxies and quasars, and x-ray emission from very hot (ten million degrees Kelvin) gas in clusters of galaxies, and detected x-ray background radiation from sources spread through the whole universe.

In this book we are going to focus on infrared and submillimetre radiation, light with wavelengths from 0.7 microns to 1 millimetre (1000 microns). Because this is a rather broad swathe of wavelengths, we often subdivide it into near infrared (0.7–3 microns), mid-infrared (3–30 microns), far infrared (30–200 microns) and submillimetre (200 microns to 1 millimetre). For reasons having to do with detector technology, we often think of the submillimetre band as extending to 3 millimetres, although 1–3 millimetres cannot really be “sub”millimetre. For astronomy what unites the whole infrared and submillimetre band is the phenomenon of interstellar dust, which absorbs visible and ultraviolet light from stars, galaxies and hot disks around black holes and then reradiates it at infrared and submillimetre wavelengths. When we look up at the Milky Way at night, we see

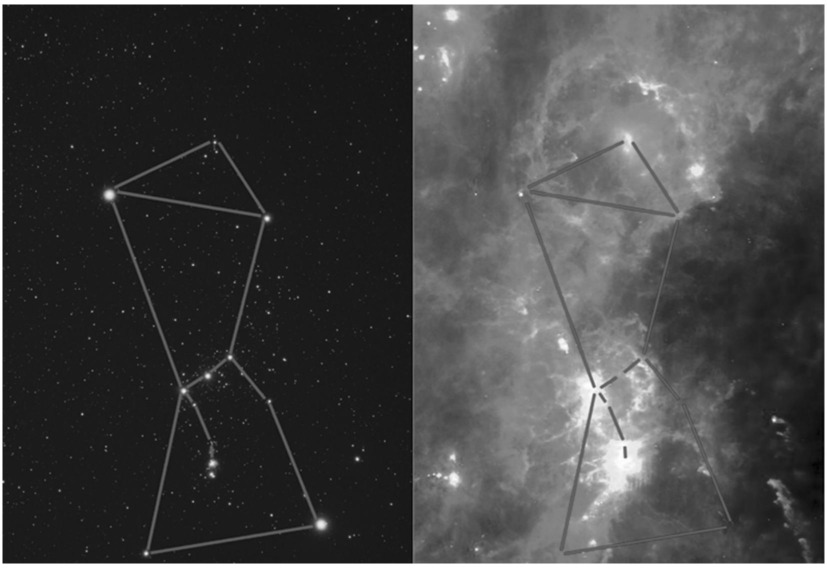

Figure 1.4. On the right is an infrared image of the constellation Orion, from the *Infrared Astronomical Satellite* mission (see Chapter 7), compared with an optical image on the left. The lower of the two bright patches in the lower centre of the infrared image is the Orion Nebula (Messier 42) in the Sword of Orion, while the bright nebulosity just above it and to the left surrounds the Belt star Zeta Orionis. The bright spot surrounded by a large ring is Lambda Orionis, and the spot just outside this ring on the left is Betelgeuse (see also Plate I).

that parts of it are obscured by dark patches such as the Coal Sack, which are in fact clouds of gas and dust. In infrared light these same dark clouds appear as bright patches of emission. In fact, about half the energy in starlight ever emitted in the universe has been absorbed by dust and reradiated in the infrared. For newly formed stars that have not yet emerged from the cocoon of gas and dust in which they formed, the fraction of their visible and ultraviolet light absorbed by dust can exceed 99%. At infrared wavelengths, we can peer into these obscured regions, so there are aspects of our world that simply cannot be appreciated without looking in infrared light. This is wonderfully illustrated by the contrasting infrared and optical views of the constellation Orion (Figure 1.4, see also Plate I). The bright stars of the visible constellation are barely discernible in the infrared. Instead we see the clouds of dust and gas from which new stars are forming.