Chapter 1

The naked-eye universe

Men at some time are masters of their fates:
The fault, dear Brutus, is not in our stars,
But in ourselves, that we are underlings.
– Cassius, from *Julius Caesar* (Act I, Scene ii)
by William Shakespeare

If you live in a big city, you have no doubt heard talk of stars. Next time you are driving across country at night or any time you are away from the city lights, stop for a while and take a good look at the sky. How many stars do you think you can see? Generally speaking, if you are in a dark enough location, you should be able to see around 1000 stars at any given time. As the Earth rotates throughout the night and stars rise in the east and others set in the west, you can increase your count to 2000, then 2001 when the Sun rises. The total number will grow further over the course of a year, with the slow motion of the Earth around the Sun. With a visit to other latitudes to see objects otherwise hidden below the horizon, the total would come to around 6000, depending on how good your eyesight is. Some of these 'stars' are in fact nebulae or even one of the five planets visible to the naked eye. The total number of objects is only slightly increased by throwing in one Moon and three galaxies. Including the odd comet and closely passing asteroid, the rare supernova, the occasional Earth-orbiting satellite, that's the entire list of objects beyond the Earth you can hope to see with the naked eye.

Given that our galaxy alone has some 10 billion stars in it, you might think that we are missing out on a lot. But our eye is doing a remarkable job even to present this view of our universe, and it is the result of much evolutionary modification. It has been theorised that the development of vision was responsible for the Cambrian evolutionary explosion some 540 million years ago. For around 3.5 billion years, life on Earth developed into just three phyla (a taxonomic grouping of plants or animals). Then, after a burst of evolutionary development lasting possibly as little as 5 million years, there were 38 phyla (which later extinctions reduced to the 35 we see today). It just so happens that natural light-sensitive receptors began to develop around this same period. Vision provides a huge selective pressure on animals to detect predators, prey, food, mates and the surrounding environment. Not surprisingly, then, eyes have developed in many different forms. Some animals are sensitive to ultraviolet or infrared radiation that we cannot see, while others have eyes specially designed for low light levels or polarised light. Even the different structures of eyes demonstrate a wide diversity: from the multi-lensed fly to the lobster, which produces images by reflection. Some creatures have zoom lenses, others have scanning optics while yet others have simple eyes which act like pinhole cameras. The eye is a remarkable piece of natural engineering, and in the case of humans, by far the most powerful of our senses.

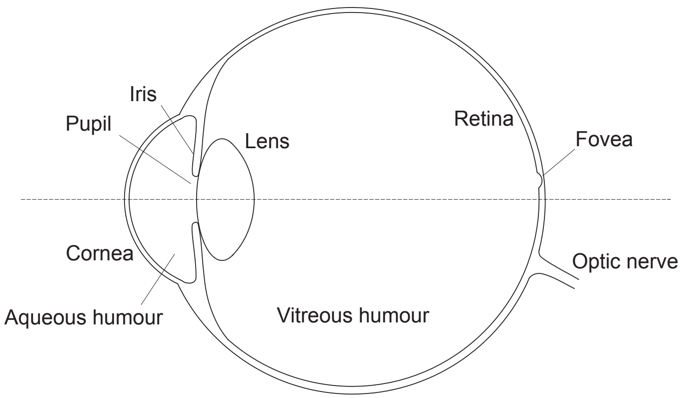

Figure 1.1: The human eye. Our best imaging takes place for light falling on the fovea which is populated mostly with colour-sensitive cones.

The human eye has many parts, but the basic design can be broken down into four major sections, as shown in Figure 1.1. There is a cornea for protection, an iris to alter the amount of incoming light and a focusable lens which forms an image onto the light-sensitive retina. The retina has two types of light-sensitive receptors, namely cones and rods. There are about 5 million colour-sensitive cones, predominantly located within a 1.5-mm diameter region called the fovea. These provide sharp imaging over a small field of view under good lighting conditions. The 100 million rods are distributed over the rest of the retina and while not able to distinguish colours, provide most of our peripheral and low-light vision.

Overall the eye is able to image at wavelengths of light (in effect defining the 'visible spectrum') from around 400 nm (violet) to 700 nm (red).[1] Individual cones are sensitive to a narrow range of colours centred approximately over the violet-blue, green and greenish-yellow portions of the spectrum. The actual colour of incoming light is inferred by the amount of activity triggered in each type of cone. For example, if the brain senses an equal output signal from neighbouring blue- and green-sensitive cones, then a colour lying midway between the two (something like aqua or turquoise) would be what the brain 'sees'. The cones are separated by about 2.5 micrometres (2.5 μm) in the fovea, so the smallest angle we can resolve under ideal conditions is around 1 arcminute (or around a thirtieth of the angle subtended by the full Moon). To put it another way, this means we should just be able to make out two distinct headlights on a car around 3 km away.

As a slight diversion at this point, it is often said that the Great Wall of China is the only man-made object visible from space. This is complete nonsense, as can easily be demonstrated. From the height of the International Space Station (350 km), an angle of 1 arcminute translates to 100 m on the ground. There are, of course, a multitude of structures larger than this. For example, the Great Pyramid of Giza, at 230 m on a side would be easily visible and appear quite separate to other pyramids nearby. On the other hand, the Great Wall is a little less obvious and most astronauts, including Chinese astronaut Yang Liwei, have said it was not visible. We will address this issue in greater detail later on, but the fact that the wall is quite long (over 6000 km) means nothing – the more important factor is that it is only 15 m wide. Under the right lighting conditions, it may show up against the background, just as we see stars at night but cannot resolve them.

This leads to another property of the eye which is truly remarkable – its sensitivity to a wide range of light levels. The eye's response to luminous flux is logarithmic, which permits us to accommodate both very bright and very dim scenes, often without even being aware of the difference. For example, you can comfortably read this book in direct sunlight, or by the light of a half-full Moon – a reduction in light levels by a factor of one million! By comparison, manufacturers of photographic film are happy with a film which can accommodate a range one thousand times smaller. Even the most advanced digital sensors would find it difficult to accommodate these extremes. Of course, the human eye cheats a little by using cones for bright light and rods for low light levels. For astronomy then, rods are the more important detector in the retina, and they lie outside our direct field of vision (the fovea). This means that to see the faintest stars it is often best to use averted vision. That is, you should look to one side of the star so that the light does not fall on the fovea, which is predominately populated with less sensitive cones. The problem with rods, of course, is that they have no colour sensitivity. This is fairly evident when you look at a nighttime scene dimly lit by the Moon, where everything loses its colour and the scene appears in shades of grey. The colours are still there – you simply can't see them.

Beyond just collecting light, the human eye forms images of distant objects. These images are produced on the retina by the lens, in precisely the same way as a camera lens forms images on film. We'll come back to the concept of imaging later, but for now we should note that by changing the tension in muscles surrounding the lens of our eye, the shape of the lens can be stretched or compressed in order to maintain focus over a wide range of viewing distances. The retinal image is actually produced upside down, but the brain does its own correction to this unreal situation and inverts everything back to normal. The brain then combines the light from two eyes which look at a scene from slightly different angles (parallax) to give us a sense of three dimensions. In summary, the human eye can be used to detect colours, shades, shapes, dimensions and distances. From an engineering point of view, the eye is a truly remarkable instrument; even more so given that it is the result of millions of years of random trial and error.

Of course, the human eye does have some limitations. We cannot see radio waves, microwaves, infrared, ultraviolet, X-rays or gamma-rays. The refresh rate of the visual signal processing (called persistence) is around 20 times a second and changes occurring faster than this cannot be seen. At the same time, we cannot brighten the image of a dim object by staring at it for a long period of time in the same manner as a time-lapse exposure on film. Another difference between the eye and cameras is that there is no way of recording our retinal views on a permanent medium for others to see. The eye is susceptible to fatigue, disease and aging, which can affect resolution, focusing and sensitivity. On top of this, the eye (or more correctly, the brain) can also be confused and fooled by certain arrangements of objects. In spite of these limitations, though, the eye is a remarkably versatile instrument.

Often when considering a telescope, people will be prompted to ask: 'Just how far can it see?' Later in this book it will become clear just how meaningless this question is, but for now consider applying the same question to our eye. You can see objects sitting right in front of your face, but at the same time you can see a mountain dozens of kilometres away. Alpha Centauri is around 40 trillion kilometres away, and Andromeda Galaxy, also visible to the naked eye in dark skies, is nearly a million times more distant than this. So really, whether the eye can see an object comes down to how big and bright the object is, not how far away it is. Of course, seeing light from a star is not the same as forming an image of it – after all, a point of light is not an illuminated disk, so this is where it becomes meaningless to consider these sorts of issues. In fact, it is because we cannot see any of their details that cosmic objects have always held such a fascination for us.

As you look at the stars, try to imagine yourself as an Egyptian sailor on the Mediterranean Sea some four-and-a-half thousand years ago. From an early age, you would have been taught how to find the dim star Thuban. Throughout the entire night, it would serve as an unwavering beacon by which to navigate. Even after the most disorientating of storms, this star always lay to the north. It is no wonder, then, that Pharaoh Khufu aligned his Great Pyramid to this most important of stars. It is in contemplating the history of naked-eye observations of the sky that we begin to appreciate why such observations have had such a powerful effect on mankind throughout the ages.

Every star (except the Sun) rises and sets around four minutes earlier every night. Over 365 days, this amounts to a complete day, so the rising or setting of a particular star at a particular time can be used as a measure of a year. The same Egyptian sailor, as a long-time observer of the heavens, would know that the rising of certain groupings of stars at dusk indicates the onset of particular seasons. This knowledge could be used to anticipate the annual flooding of the Nile and for planning harvests and plantings. To nomadic civilisations, accurate timekeeping was equally important for following migratory animals and preparing for the harsh environmental conditions of particular seasons. As civilisations developed, crop rotations and agricultural storage requirements were determined by a 'calendar' which was essentially a measure of the motion of the stellar sphere.

Naturally it was easy to believe that these groupings of stars were not simply passive markers of time, but exerted an active influence over life on Earth. These groupings (asterisms or constellations) were associated with physical objects or gods as long ago as 4000 BCE, and from there it was a small step to anthropomorphising their forms. The constellations thus became powerful gods influencing our lives, which inevitably led to religious and superstitious rituals and beliefs. Temples were built and offerings and sacrifices were made to influence the gods to provide bountiful harvests and improve living conditions. These gods were regarded as powerful enough to control human existence, so they were not to be trifled with. The intertwining of superstitions and religion continued even into the modern era. For example, the Catholic Church used astrological charts until well into the eighteenth century.

While many people still believe in astrology today, it clearly makes no sense. The constellations used for astrological ‘signs’ are merely apparent groupings of stars which are actually unrelated and lie at completely different distances. They have no physical existence – you could never ‘visit’ a constellation. Furthermore, there are three planets which are used in present-day astrology whose existence was not even known before the eighteenth century, so those who purport to be using ‘ancient mystical knowledge’ are relying more on the gullibility of the uneducated than on any secrets of civilisations past. It is also worth mentioning that there are in fact 13 Zodiacal constellations, with Ophiuchus lying between Libra and Sagittarius.

While the stars appear to move around us, their motions are really only telling us where we are and what time it is.

The Chinese, well aware of the ‘clockwork’ nature of the celestial sphere, used the apparent motions of the Moon and the Sun as the basis of their calendar. A Chinese year can have 353, 354, 355, 383, 384 or 385 days on a cycle which repeats every 60 years. It may seem a little confusing and cumbersome at first, but it works. Proof of this is the fact that the Western year 2006 CE is year 4703 in the Chinese calendar. In fact, it is the longevity of this calendar which has made it possible for historians to examine Chinese records to determine accurately the precise dates of ancient events, both celestial and social. Likewise, the Jewish and Muslim faiths have, for centuries, used the cycles of the Moon for daily observances and calendrical measurement. The Hebrew calendar date for 2006 CE is 5766 AM (*Anno Mundi* – in the year of the world). By comparison, the Gregorian calendar seems positively newfangled. It also puts into perspective all the superstitious fuss that went along with the dawning of the third millennium.

I was once observing a transit of Mercury across the Sun with a student who remarked on the amazing punctuality of the event. Quite the opposite, I pointed out, she should be more amazed that our clocks are timed with such precision to celestial events. After all, this is where we get our system of time measurement. In fact, measurements of the passage of certain stars across a 'fixed' point or line in space were used to determine the length of what would become our Gregorian calendar year. While the actual tropical year is determined by the Sun, a rough approximation can be made by measuring the time between successive transits of a given star across an arbitrary north-south line in the sky at a certain time of the day. For example, if you have a telescope aligned north-south, and Vega is centred in your view at exactly 9 pm, then it will be centred again at the same time a year later.

An example of the clockwork precision of celestial motions was never more evident than at the turn of the sixteenth century. While on his fourth voyage to the New World, Christopher Columbus became stranded in Jamaica. At first, Columbus and his crew were well received by the locals, who fed and housed them while they waited for a rescue party. However, as the months passed, he and his badly behaving crew became increasingly unpopular with the indigenous population. Relations degraded to such an extent that there was a distinct possibility of a bloody confrontation. Sensing this, Columbus invited the chiefs to a meeting with him on 29 February 1504. Columbus stated that God was unhappy with their treatment, and threatened to remove the Moon from the sky. That night, as Columbus well knew, there was to be a lunar eclipse. Sure enough, as foretold, the Moon began to darken and redden. The natives, understandably impressed and more than a little terrified, begged Columbus to get his God to return the Moon. Columbus 'pondered' their request for a while and eventually agreed to do so (he could afford to play it slow as a lunar eclipse can last for hours). From this point onwards the locals pretty much did his bidding until the rescue party arrived several weeks later.

Astrometry, the measurement of stellar positions, is also essential for navigation. Throughout the course of the night, the stars in the sky will rotate about the celestial pole. In the Northern Hemisphere, this point in the sky is very close to Polaris (the North Star or Alpha Ursae Minoris). Taking a long-exposure photo of the night sky towards either pole will demonstrate this, as shown in Figure 1.2. The Earth also has a slight wobble, which causes its axis of rotation to precess (describe a circle) over a period of 25,800 years. Around 4500 years ago, the north celestial pole lay near a star called Thuban, but today it is close to Polaris. In fact, precession will continue to narrow the angle between them until 2106. But even now, Polaris serves as a much better guide to true north than magnetic north measured by a compass. This relationship is quite fortuitous (and unlikely) and in the Southern Hemisphere there is no bright star close to the south celestial pole.

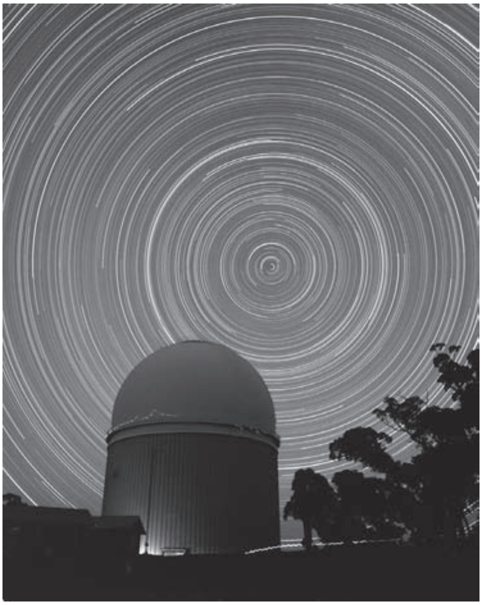

Figure 1.2: Star trails around the south celestial pole. Over the course of evening (and the day too), the stars appear to move around the celestial poles. A time-lapse photo shows this motion as the stars form circular star trails. The shorter trails are nearer to the pole. Courtesy: Anglo-Australian Observatory.

While navigators can get their bearings (compass orientation) from the celestial poles, knowing your current location on the Earth is also critical for navigation. For this we can use the celestial poles once again. Quite simply: the angle of the pole above the horizon is your latitude. Live in Oslo? Since your latitude is 60 degrees North, Polaris is 60 degrees above the horizon, or a third of a way around the sky. Longitude is much trickier to determine. In order to know how far you are east or west of the Greenwich meridian, you essentially need two clocks – one telling you the local time, and one telling you the time it is in London. For each hour's difference between the two clocks, you are a further 15 degrees removed from zero degrees longitude. So, if your local time is four in the afternoon and it is noon in London, then your longitude is 60 degrees East.

For millennia, navigators had been able to measure latitude, but it was not until towards the end of the eighteenth century that John Harrison developed a sufficiently accurate timepiece for longitude measurements at sea. For accurate navigation today, we mostly use the Global Positioning System that consists of 24 or so satellites in precisely known locations. GPS uses the relative timing of signals from atomic clocks on these satellites to determine position (latitude, longitude and even altitude) on the ground. These days there are international organisations that exist to take care of the details and help us better define time and location to the n^{th} decimal place. Before the invention of the telescope, however, people had to rely on less scientific authorities to determine such things in their lives.

At the turn of the sixteenth century in Europe, the Catholic Church had pretty much determined the way things were in the universe. Following a strict Ptolemaic doctrine, there were several assertions which were not up for debate. The Earth was the centre of the universe (by virtue of it being the ultimate work of God), and the planets and Sun all rotated around it in circular orbits. All bodies in the universe were perfectly spherical and except for the odd comet, the celestial sphere was permanent and unchanging. Over much of the Dark Ages, this simple arrangement was immutable. But as measurements of planetary positions improved, adjustments had to be made to make doctrine agree with reality. For example, the planets simply refused to move in precisely circular orbits about the Earth. In order to correct for this, some planets were permitted to travel in small circles about a point which itself moved in orbit about the Earth. This stop-gap measure worked up to a point, but it was becoming clear that further improvements were required. So it was that in 1540 Nicholas Copernicus published *De Revolutionibus* with the primary tenet being that the Sun, not the Earth, was the centre of the universe.

The Sun-centred model solved many nagging problems associated with planetary motions but was still far from perfect and often required as much tweaking as had the Earth-centred model. Fortunately for Copernicus (depending on how you look at it) he died within days of the publication of this work, and so did not have to answer for any of the subsequent controversy. While it was not widely read, the main thesis was discussed widely around Europe. For the most part, the Church largely ignored it or at least treated it as an annoying work of fiction. After all, there were no gross errors in the motions of nighttime objects that could seriously threaten the basic canonical law and besides, the Sun-centred model was not new, but had in fact been suggested by Aristarchus (and reported by Archimedes) at some time during the third century BCE. Since the Church was able to ignore this for nearly a millennium, the resurgence of the idea was no great cause for concern.

Tycho Brahe[2] is perhaps one of the last of the pre-Enlightenment 'scientists'. His life work consisted almost entirely of observations and cataloguing of phenomena without much effort to devising an underlying theoretical framework to describe the 'why' behind the phenomena or making predictions for testing these theories. However, this should not diminish his achievements in any way – far from it. In fact, his observations were of such a high quality that they were used by his assistant to devise the first laws of motion of planetary bodies, which are still used today. And he did all this without the aid of a telescope.

Brahe was born in Skane, Denmark (now in Sweden) and raised by his aristocrat uncle in an environment which emphasised education and critical study. Early on, perhaps as the result of observing a partial eclipse in Copenhagen, Brahe became intrigued with celestial observations and the ability of astronomers to predict such events well in advance. Throughout his early life, he studied at various universities, eagerly pursuing a future in the sciences. In his day, most astronomy was actually astrology, and Brahe made a name for himself when he used a lunar eclipse of 1566 to correctly 'predict' the death of Suleiman the Magnificent, ruler of the Ottoman Empire. Since Suleiman was 72 years old, it may be said that this 'prediction' was not much of a stretch, and it was even less impressive when it was later discovered that Suleiman had actually died a few weeks before the eclipse – but word of this had failed to reach the Danish court. A further significant event in Brahe's early life occurred when the tempestuous young man got into a duel that resulted in him losing a portion of his nose. For the rest of his life he covered up this disfigurement with a prosthesis of gold and silver. Much of his early work is fairly unremarkable, except perhaps for the fact that his studies gave him a good knowledge of the heavens. This would prove to be instrumental in a discovery that would bring him his fame.

On the evening of 11 November 1572, Brahe noticed a new star in the Constellation Cassiopeia. Over the next few months, he continued to observe the star and eventually published his findings in *De Nova Stella* (About The New Star). While others had observed the star, Brahe made the bold assertion, on the basis of his measurements, that this was indeed a new object and not a new comet or meteor which were the only other known objects that could appear in the sky. His revelation should be viewed in the context of the time in which he lived. It has already been mentioned that the Catholic Church had held steadfast to the view that the heavens were perfect and unchanging. Brahe's new star challenged this prevailing doctrine and could not be ignored. Such was the impact of this work that today we still refer to similar events as 'novas' (and supernovas, which is in fact what Brahe's new star was). For Brahe personally, the acclaim the work received had more immediate financial benefits, when he managed to parlay it into a Royal tenure. The King of Denmark gave him a generous income and support for the creation of Uraniborg observatory, which Brahe built on Hven, an island near Copenhagen. While not quite what we think of as an observatory in today's terms (as there was no telescope), it was a site for observing and documenting the heavens in a consistent manner.

To aid his observations, Brahe constructed a fine quadrant which could measure the altitude of stars above the horizon to great precision. For the rest of his life he made copious measurements of the positions of celestial objects and it is for these measurements that Brahe should be noted. While to most people they resemble a tedious catalogue of numbers, they far surpassed the accuracy of any previous measurements. Most were good to a couple of arc minutes, and some to better than a quarter of this – something which can be compared to the size of the printed words on this page on the other side of a large room. It was as a direct result of these unprecedented observations that his assistant, Johannes Kepler, was able to formulate his laws of planetary motion.

Kepler was a long-time supporter of the Copernican Sun-centred universe theory but lacked the eyesight for the high-quality observations required to evaluate the theory. Over many years he sought to work with Brahe (or rather, his data) and was eventually hired as his assistant early in 1601. Brahe was very protective of his measurements and would only allow Kepler to look at limited portions of it. This all changed when he died later that year and Kepler inherited the valuable catalogues. With his gift for mathematics, Kepler was able to use the data to formulate three laws of planetary motion (published in 1609) which went a huge way to legitimising the Copernican universe. The three laws are:

1. The orbits of planets are ellipses, with the Sun at one focus of the ellipse.
2. As the planet moves in orbit about the Sun, the line joining the planet to the Sun sweeps out an equal area in an equal time.
3. The ratio of the squares of the orbital periods of two planets is equal to the ratio of the cubes of their semi-major axes.

The underlying physical reason for these laws being the way they are was not really understood until Newton formulated his Theory of Gravitation some 50 years later. However, these simple laws made it possible to accurately predict the motion of planets, and are still used today for all but the highest precision orbital calculations. Kepler's work was incredibly important, and began a gradual change in opinion away from the Earth-centred universe theory, and from the unquestioned acceptance of religious dogma. Alone it would have caused an upheaval in the way the world viewed the universe. However, even as it was being prepared for publication, an optical worker in Holland had invented a device which would dramatically increase the pace of inquiry into the physical universe and usher in the Enlightenment.