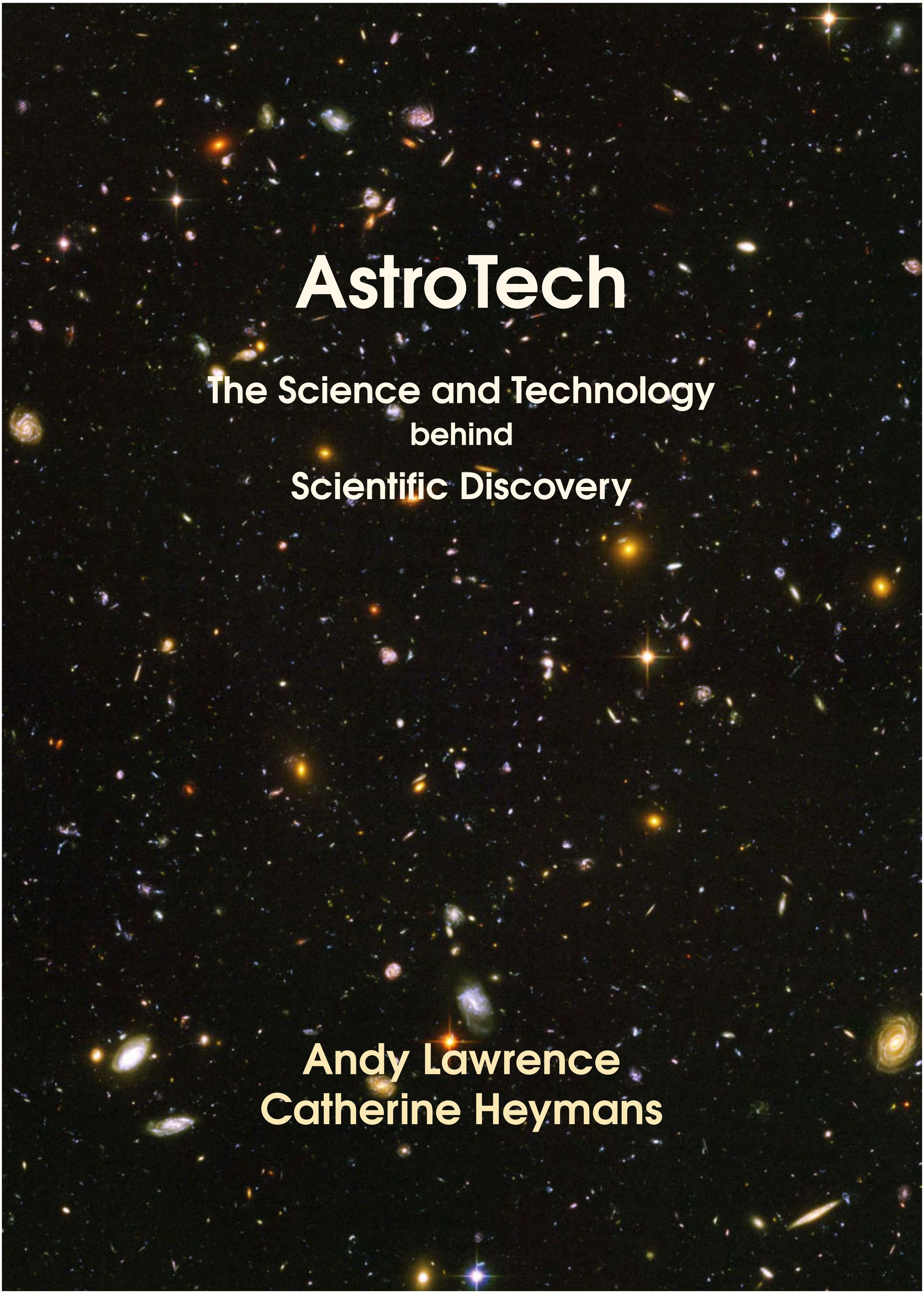

AstroTech

The Science and Technology behind Scientific Discovery

Andy Lawrence
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EARLY DRAFT!! Reader beware

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Preface

This book came out of our feeling that a large audience of intelligent and curious readers were not being well served by most books about astronomy. These books seem to divide into two types. The first type of book is the textbook intended for undergraduate and graduate students. There are many marvellous examples of such books, but they assume a lot of pre-knowledge and mathematical background, and a large amount of study time at the student's disposal. There are of course easier textbooks intended for non-science students, but they tend to be very voluminous (and expensive!) and still assume full time study.

The second type of book is the popular astronomy book. Again, such books can be wonderful, but they are usually essentially entertainment, keen to portray the wonders of the universe, and to be as mind-bending as possible, while not demanding too much of the reader in either background or time. When we read popular science works outside our own specialism, we quite often find such books frustrating. We stop and think "well that's amazing - but how do they know that?" Our feeling is that there must be large numbers of people having a similar reaction to popular astronomy books.

So the challenge is to write something for readers who are seriously interested in understanding how science *really* works, but who don't want or need a full-time University level course of instruction. What is missing from popular books that such people might want? We can think of three things. The first is an overall sense of straight forwardness - trying to explain what really happens, as opposed to giving a flavour, or using metaphors. Throughout this book, we try to go for the concrete, as opposed to the warm and woolly.

The second thing missing is just a little bit of mathematics. There is a tendency to assume that either you use full blown gory undergraduate level maths, or you have to steer clear of maths as if it were a plague. But lots of people have reasonable high-school level maths, even if its a bit rusty. If you put some numbers in, things can become so much clearer.

The third thing often missing in popular astronomy books is links to more material, for readers who want to go further. Some scholarly areas are rather better at this - there are good semi-popular works on evolutionary biology and on history, with extensive notes and reading lists - but you don't see this often in popular astronomy books. We don't want to make our book like a giant laundry list of references, but many people are keen to explore, and in the internet age this urge should be easy to satisfy.

We were having these thoughts about a different kind of astronomy book, when the MOOC phenomenon took off. A “MOOC” is a Massive Open Online Course - a short educational course typically composed of videos, quizzes, discussion forums and information pages. Edinburgh University has worked within the Coursera partnership to put together a number of such courses in a range of subjects, attracting huge numbers of students from all over the world. We jumped at the chance to make "AstroTech - the Science and Technology behind Astronomical Discovery". There are other Astronomy MOOCs, so we decided to focus ours on the links between technology and science, and to give it a “how its really done” flavour. The first run of the course was in April 2014, with 21,000 students participating. It was hard work to put together, but one of the most exciting things we have ever done - the buzz on the Forum was wonderful, and so many people seemed so grateful.

The success of MOOCs demonstrates that there is indeed a hunger for something that is more satisfying than simple entertainment but less demanding than full time study. However, even a MOOC can be challenging, with large drop-off rates during many courses. Because of this, we decided to make our MOOC less onerous in time or achievement than some others we had seen. This was a success, in that we had a high completion rate, and many grateful comments. However, some students were clearly frustrated, because once they started learning, they really wanted more!

We decided that the way to satisfy these students was to go back to the idea of a book, to supplement the MOOC. So here it is. It follows the same structure as the course, but goes a little deeper. The book stands alone, so you don’t need to take the MOOC. But if you are taking or have taken the MOOC, we hope you find this a useful companion.

Whoever, you are, we hope you find the book a useful and enjoyable read.

Edinburgh,
May 2015 *Andy Lawrence, Catherine Heymans*

Acknowledgements

Many thanks to all the people who helped us put the original MOOC together - the Edinburgh Coursera team, especially Tim Askew, Imogen Scott, and Amy Woodgate, and the our team of TAs, Beth Biller, Nathan Bourne, Alastair Bruce, Andrew Davis, Pratika Dayal, Duncan Forgan, Richard George, Cass Hall, Shegy Parsa, Lee Patrick, Rosie Shanahan, and Vanessa Smer. Thanks also to the thousands of students who helped make the course a success - the Forum discussions were amazing!

Contents

1. Science and Technology: joined at the hip

We know a lot more about the Universe than we did five hundred years ago. How did that happen? Is it because a succession of brilliant scientists had deep new ideas? Or because a series of careful astronomers stared at the sky and made new discoveries? Well, both those things happened, but how did those astronomers manage to see what others had not seen before? Nearly always it was because some new technology came along that made new observations *possible*. What drove that technological development, pushing research innovation to the limits, were the deep thinking scientists who wanted to test out their new ideas. So to a large extent, technology and science have progressed together, tightly linked. That is the theme of this book.

1.1 Our Knowledge of the Universe

With over 7 billion people bustling about on planet Earth, and no sign of life elsewhere in our solar system, we may consider the human race to be rare, unique and one of a kind. But in our own Milky Way galaxy there are around 350 billion stars; 50 stars each for every single human being on planet Earth. In the Universe there are over 100 billion galaxies. The existence of planetary life is a lottery, but with so many planets in the Universe, it's highly likely that we're not alone.

We know some amazing things about the Universe that we're going to explore in this book. We know that the chemicals that we're made up of could only have been formed in the hot fiery core of a star, that in its death throes created the gas cloud which our solar system then formed out of. In our own solar system of planets there are also millions of killer rocks out there that might one day obliterate planet Earth. We know that the first galaxies in our Universe formed over 13 billion years ago, and that the galaxies that we see today have a massive black hole at their centre. We know that our whole Universe is expanding, but mysteriously that expansion is getting faster and faster every day.

How do we know all this? Astronomy is the science of the largest distant scales, the longest time scales, and the most extreme environments in terms of temperature, pressure and density. Now unlike biologists and chemists, we can't create an experiment in a laboratory to test these extreme conditions. Astronomy as a science can only observe what the Universe chooses to reveal, and that is through light.

1.1.1 Light

Light is a concept in physics that is often deemed too mysterious to think deeply about. Every waking moment of your life though, light is being collected by your eye and through a series of chemical and electrical events the information carried by that light is transferred and interpreted by your brain. Light is central to our every day lives, and the key to exploring the Universe.

To understand light we must first consider the fundamental forces in our Universe. These forces can be thought of as the rulebook which all physical processes in the Universe must follow. The fundamental force that you are probably most familiar with is gravity. It's gravity that keeps us stuck to the ground. As we move further away from the Earth, the strength of that force decreases which is how astronauts end up flying around in outer space. We say that the force is 'carried' by a Field. The gravitational field around the Earth, just tells us the strength of the gravitational force at each point in space. At this point reader, I'd like to ask you to stand on a chair. The gravitational field up there is slightly weaker than it was when you were sitting in that chair. You had to expend a small amount of energy to work against gravity as you climbed. Now I'd like to ask you to step off the chair, taking care that all small animals and children are at a safe distance. Provided the fundamental forces hold in your house, you should have dropped to the floor moving at quite a fast rate. The pull of the force of gravity gave you energy as you fell. So force and energy are linked.

Let us now turn our attention to the second fundamental force called electromagnetism. This is a combined force that can be felt from moving charged particles, for example electricity, and also magnets. I'd advise the reader not to play with electricity, but if you have some magnets at home, I do encourage you to experience the force between them. It is something that we cannot see, but, in a similar way to our chair experiment, we can feel the pull of the electromagnetic force on the two magnets. The change in strength of the force as the two magnets are attracted together or repelled allows us to experience the energy given to them by this force field.

Light transports energy from one place to another. It does this by varying the local electromagnetic force field as it travels along. As light leaves the screen that you are currently reading and travels towards your eyes, what it's doing is changing the strength of electromagnetic force field between the screen and your eye. Alternating by increasing and then decreasing the strength of the force field, the energy travels through space as a water ripple would travel across the surface of a pond after a pebble has been thrown in. And that is all light is, a vehicle to transport energy using the fundamental forces of nature to do so.

Physicists like to categorise light in terms of the energy that it is carrying. Starting with the lowest energy, perhaps you listen to a radio or a friend talking on a mobile phone. These pieces of technology collect very low energy radio light, emitted from the masts and transmitters that you'll see around town, and then coverts it into sound that your ear can then interpret. Next comes the infrared light which you will be emitting because you are hot. Being able to detect infrared light permits some level of night-vision and those eery green military videos that are sometimes shown on the evening news. The human eye can only see in optical light that you're reading with at the moment. Then there is ultra-violet light, responsible for all cases of summer sunburn. Finally we come to the most energetic X-ray and gamma ray light, emitted from rare objects in the Universe such as a massive supernova explosion.

To understand the Universe, astronomers have to observe in all of these different types of light, and each type of light requires a new revolution in technology.

1.2 Revolutions in Astronomy

A series of technological revolutions has helped astronomy to take enormous leaps forward. We are going to simplify history a little, and divide it into six key developments.

1.2.1 Revolution Number One: The Telescope

The invention of the telescope allowed us to see finer detail, and fainter objects in the sky. Originally, all we could do is stare at the sky with our eyes. Astronomers (or sailors) could sight along devices like quadrants and get accurate directions of stars, which was why ancient astronomy was all about the positions and motions of stars and planets - but those stars and even the planets were just points of light. What happens when we look at a star? Light passes through the aperture of the eye (the pupil) and then the lens focuses the light to form an image on the retina. The eye works pretty much the same way as a camera. With the telescope, the glass lens does the same job as the lens of the eye, collecting and focusing the light. If you put a piece of paper behind that lens, you could get the image straight away. However, for your own eye to look at it, you need to straighten the light out again first; this is what the eyepiece does. (Roughly speaking, your eye expects to work with parallel light from distant things, not converging light).

The first telescopes were toys sold in Dutch market places, but Galileo was the first to see the opportunities for both science and warfare. Soon he had discovered the phases of Venus, and the moons of Jupiter, and opened up a whole new chapter in our understanding of the Universe. But if the telescope first makes the light converge, and then straightens it back again, how has that helped? There are two key things - the telescope is both longer and wider than the eye. Here is the rough idea.

First, length. When you form an image with a longer tube, i.e. a longer “focal length”, the image is more spread out, and it is easier to see fine detail. This is how Galileo was able to see that Venus was sometimes a crescent rather than a disc. Of course this *magnification* is also the crucial thing for terrestrial use of telescopes, for example recognising the flag on a distant ship. Over the next few hundred years astronomical telescopes got longer and longer, culminating in the “Parsonstown Leviathan” - a telescope in Ireland that was 54 feet long. However, there is a natural limit to this process. Both the telescope and our atmosphere *blur* the image. If you magnify the image beyond a certain point, all you are doing is making the fuzzy blobs look bigger - you can’t actually see any more detail. Modern telescopes are still quite long, but length is no longer the key issue.

Second, width. The pupil of the eye is 5mm across. A small telescope lens might be 5cm across - ten times the width, and so a hundred times the area. This means that it catches more light, and we can see fainter things than is possible for the unaided eye. This is how Galileo was able to discover the moons of Jupiter, and realise that there are things in the Universe that we didn’t even know existed at all. A modern professional telescope might be 5m across. Thats 5000mm compared to the 5mm of the eye, and so it catches a million times more light. Aperture size continues to be the obsession of modern astronomy. In this case the limiting factors are engineering and money. It is very hard, and very expensive, to make very big telescopes. We will pick up those challenges in Chapter 2.

1.2.2 Revolution Number Two: Spectroscopy

Isaac Newton was the first scientist to use a prism to split light up into its component colours - a spectrum - and indeed to realise that natural light is actually a mixture of light of different types. Today we use diffraction gratings rather than prisms inside our spectroscopes, but the principle is the same. We now understand that those spectral components are actually light waves of different wavelength. We can learn an enormous amount from analysing the mixture of components in the spectrum. The relative amounts of red vs yellow vs blue can tell us about the temperature of a radiating body, or the surface properties of a reflecting body. The presence of dark lines in a specific pattern can tell us which elements are present. For any given element the wavelengths where the dark lines fall make a distinct mathematical pattern, which is a clue to the nature of atoms themselves. Spectroscopy is a key tool in physics, chemistry, biology, forensic science, and so on.

Unlike the telescope, it was actually quite a long time before the spectroscope had an impact on astronomy.

Dark lines in the spectrum of the Sun were first noticed by William Hyde Wollaston in 1802, and then studied in more detail by Joseph von Fraunhofer in 1814. Decades later, Kirchoff and Bunsen were able to see the same dark lines in laboratory experiments. This told us that the Sun is made of the same sort of elements we see here on Earth. An interesting exception was a mystery line seen in the spectrum of the Sun by Janssen and by Lockyer. They correctly deduced that this was due to a new element - coined “Helium” - that was present in the Sun, but until then, hadn’t been seen on Earth. (We now have plenty of Helium balloons!). Many decades later, two astronomers - William Huggins in London and Alberto Secchi in Rome - had the idea of attaching a spectroscope to a telescope and pointing at the stars. Secchi noticed that stars fell into groups with different patterns of dark lines, and thus started the study of stellar structure and evolution. Huggins noticed that nebulae (gas clouds) had glowing *bright* lines rather than dark lines, and thought he had discovered another new element, which he named “Nebulium”. Decades later, physicists realised that the Nebulium line was actually due to Oxygen behaving differently in the very low density gas of interstellar space; this behaviour was a big clue in understanding atomic physics, and from there to understanding how stars work.

Spectroscopy caused the transition from *astronomy* - concerned with positions and motions - to *astrophysics* - concerned with how astronomical objects work. With spectroscopy we can tell what stars are made of, how hot they are, and even how fast they are moving. In Chapter 6 we will look at how this works in more detail.

1.2.3 Revolution Number Three: Detectors

Once a telescope (or a simple camera) has focused the light and formed an image, you need some way to *detect* that image. That is what the retina does in the human eye; as the light arrives at the retina, it causes electrical signals which are then transmitted to the brain. The next great revolution in astronomy was all about replacing the retina with an external detector - first by a photographic plate, and then more recently with semi-conductor devices like the CCD. Once again, the new technology was not invented by astronomers themselves, but they jumped on the opportunity, and it transformed astronomy.

Why did replacing the eye with a photographic plate make such a huge difference? There are two key issues. The first is that photographs enabled astronomers to *record* the image permanently and objectively. You don’t have to rely on a verbal report, or a sketch. Once you have taken a photograph, you can show it to anybody else, and you all see the same thing. The second key difference was that you could *integrate*, i.e. you could keep adding up the effect caused by the light over a long exposure. When viewing a scene with the human eye, we have the impression of a continuous movie, but actually its a series of exposures each of which is about 1/25th of a second long. With a photographic plate you can expose for much longer - minutes or hours - provided you can keep the plate steady of course. Pretty soon astronomers were keeping their glass plates bolted to the back of the telescope and exposing the whole night. The effect was dramatic. With long exposures you can see much fainter objects.

Nowadays of course, both in astronomy and in our cameras, we no longer use photographic plates, but electronic devices such as the ‘Charge Coupled Device (CCD)”. In Chapter 4 we will look at how they work. CCDs have two further advantages. The first is that they are much more *efficient*. With a photographic plate only about 1% of the impinging photons actually cause any plate blackening. With a CCD, typically about 80% of the incoming photons are recorded. This means you can see the same faint objects in a much shorter time, or of course in the same exposure time, you can see much fainter objects. The second advantage is that because the effect caused is electronic rather than chemical, we can feed the results straight into a computer as set of *numbers*.

If we take a series of exposures, we can store the numbers, and later on add the numbers together. Its as if we can make a giant exposure. And indeed these days astronomers sometimes "stack" data from the same piece of sky taken over hundreds of different nights.

1.2.4 Revolution Number Four: Multi-wavelength Astronomy

In the twentieth century, the universe seemed to get a whole lot weirder. We discovered things that we had no inkling of before - spinning collapsed stars, relativistic jets shooting out of quasars, hot gas at millions of degrees, and many other strange things. This happened because of the great twentieth century revolution - multiwavelength astronomy.

Light is an electromagnetic wave in space - the electric and magnetic fields in space waggling up and down from spot to spot. The length of those waves can be very different - great big metre long waves, or tiny nanometre sized waves. What we normally think of as "light' is actually a very narrow range of wavelengths that our retinas happen to be sensitive to. But there is much more out there - radio waves, infra-red, ultra-violet, X-rays - they are all light, but of very different wavelengths. There are astronomical objects out there emitting all these different kinds of waves, but we had no idea, because our eyes couldn't see these waves.

We need a different technology to "see" each of those types of electromagnetic waves. For example, radio waves cause an oscillating current in a conducting wire - an antenna - which we can then detect and record electronically. Infra-red light on the other hand can be absorbed in a small block of material and cause it to warm up very slightly, an effect which we can measure. Our light waves actually come in small packets we know as "photons", which are more or less particles of light. For X-ray light, those photons are energetic enough to ionise atoms in a block of material; in a radiation detector we can actually see the X-ray photons arriving one by one. In each of these cases, just as with the invention of telescopes and photographic plates, astronomers did not invent the technology, but they recognised its importance and used it. One by one, we opened up new "windows" on the Universe, and what we saw transformed our understanding of what was out there.

1.2.5 Revolution Number Five: Space Astronomy

The multi-wavelength revolution was closely connected with our next revolution: the move to performing astronomy from space. The ability to launch rockets into space, and to build spacecraft that can make measurements remotely, and communicate their results to the ground, has made a huge difference to astronomy. But, as we shall discuss in Chapter 3, working in space is very difficult, and whats more its very expensive. What is it about going into space that makes such a difference?

If you are a planetary scientist, then of course the answer is obvious. You can actually visit those planets. But if we are studying stars and galaxies, all we can do is stare, just as we do on Earth. So why is it better? The answer is that it is much better because we can get away from the Earth's atmosphere. The atmosphere is our enemy. It does three bad things.

The first bad thing is that it *blocks* some kinds of light. If you are interested in X-ray astronomy, you simply have to go into space. X-rays emitted by distant objects travel all the way to Earth only to be swallowed up at the very last moment by the atoms in our atmosphere. The second bad thing about the atmosphere is that it *distorts* the incoming light. As light waves travel through the atmosphere, they bend slightly to and fro. The result is that what should be pin-sharp images of the stars instead become blurred. Pictures taken by the Hubble Space Telescope can reveal detail that is completely lost in pictures taken from the ground. The third bad thing about the atmosphere is that it *glows*. It is much harder to see very faint objects if they are lost in the glare of light from the sky. As well as getting sharper pictures, the Hubble Space Telescope can see incredibly faint objects that are hard to detect from the ground.

So even though space astronomy is very expensive, it pays dividends once you get up there.

1.2.6 Revolution Number Six: Computers

The final revolution is the one we are in now - the Computer Revolution. The impact of computing in astronomy began in the 1960s, but really took off in the 1980s, and continues to accelerate to this day. Above we discussed how the invention of the photographic plate enabled us to record images permanently and objectively. What modern detectors give us in addition is the ability to record the images electronically as numbers. Once we have electronically stored numbers, we can feed these into a computer, and then we can do more or less anything we like with those numbers - we can do calculations, we can one image to another, we can move the image to another part of the world in a fraction of a second, we can zoom and rotate etc. These things now seem trivial to a modern consumer with a smartphone, but in the 1980s they were almost magically transformative.

At the same time as observers were playing with their detectors and computers, the theorists were also exploring the power of computers. Theorists took extremely big and powerful computers and ran calculations that *simulated* how the universe should look if their theories were correct. In fact pretty soon they simulated how entire universes should look, and tried changing parameters in their models - for example, if we assumed a mean density twice as large, how would that change how the universe evolved? And which version ends up looking like the actual universe we live in?

Right now we are facing a new and interesting challenge. The volume of astronomical data, and the number of different datasets, is growing all the time. If we are not careful, astronomers will spend all their time trying to understand how you work with the data from eighty seven different web sites and so on. The challenge is to standardise how data access works, and so join together the data across the world into a seamless whole. This vision is known as the *Virtual Observatory*.

1.3 Why Astronomy is hard

We have seen that a series of technological revolutions caused a series of breakthroughs in our astronomical knowledge. But why did those breakthroughs *neeed* that new technology? Well, astronomy is very hard to do. It involves some pretty extreme quantities, and difficult measurements.

1.3.1 Faint Objects

The first big problem is that, with the exception of the Sun and the Moon, astronomical objects are rather faint, and cover a huge range in brightness. There are two factors in play. The first is the *luminosity* of an object - how much energy per second it emits, in the form of light, in total. A powerful quasar can be a trillion (a million million) times as luminous as the Sun. The second factor is the distance of the object. A candle could be hard to see if its 30 metres away, but likewise a powerful searchlight could be hard to see if its 30km away. In just the same way, a small rock thats near to the Earth could be hard to spot - but so could a powerful quasar if it is right out at the edge of the observable universe.

Fig. 1.1 shows the light spreading out from an object whose luminosity - the amount of energy emitted per second - is L. When the light gets to a distance D, that energy L is spread over a sphere of surface area $4\pi D^2$. Now imagine that we are catching the light with some sort of detector (our eye, a CCD, etc) that has area A. The perceived brightness of the object depends on the flux F of energy per second through our detector. If you consider the same detector placed further and further away, it is catching a smaller and smaller fraction of the original luminosity L. The flux we get is $F = L \times A/4\pi D^2$. This is the famous "inverse square law". An object that is a hundred times further away will be ten thousand times fainter.

The Sun is pumping out *huge* amounts of energy - something like the equivalent of ten billion atomic bombs exploding every second. But we are roughly 1.5×10^{11} metres from the Sun; this distance dilutes the energy a lot, so that one square metre at the surface of the Earth catches about 1.4 kW each second. (Thats on a clear day at the equator at noon... the answer in Scotland is somewhat less...) Now lets think about the star α Centauri. It is nearly the closest star to the Sun - its companion Proxima Centauri is slightly closer. α Centauri is very similar to our own Sun, and so puts out a very similar luminosity; however, it is 270,000 times further away from us than the Sun is, and so it appears 73 billion times fainter than the Sun. You can still see α Centauri with the naked eye. However most of the stars in our Milky Way are tens of thousands of times further away, and so hundreds of millions times fainter. You can only see them with big telescopes, and then only the most luminous ones. Measuring the light from astronomical objects is very hard.

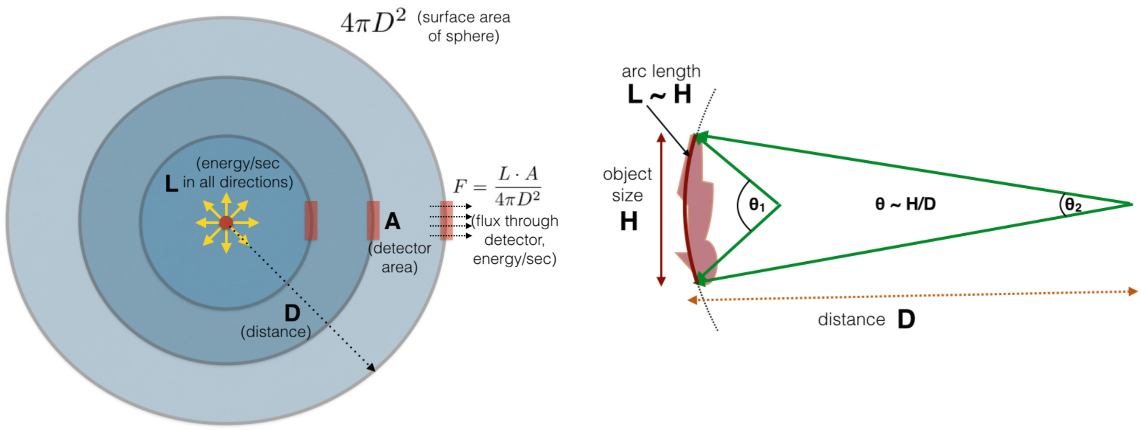


Figure 1.1: **Left** *: How perceived brightness changes with distance. An object emits a total amount L of energy per second into all directions. At distance D, the amount of energy per second flowing through a detector with area A is $F = LA/4\pi D^2$. The brightness of an object is therefore inversely proportional to the square of distance.* **Right***: How perceived angular size changes with distance. An object of size H is roughly the same size as the arc length L for a circle centred at the distance D of the observer. Angular size is therefore inversely proportional to distance.*

1.3.2 Extreme Angles

Astronomy is all about angles. We can't directly measure the size of an astronomical object in metres. All we can do is to measure the angle it subtends on the sky, as seen from where we are. Sometimes we want to measure quite big angles - for example looking at the structure of the Milky Way from one side of the sky to the other - but more often our concern is to measure the smallest angles we can. The sharpness of our pictures depends on the smallest angles we can discern. Now, just as more distant objects are fainter, they are also seen as much smaller angles on the sky, as shown in the right hand side of Fig. 1.1.

When we are doing calculations with angles, it is is easiest to work with angles in units of *radians*. An angle of one radian is the angle such that if you draw the corresponding arc of a circle, its length is the same as the radius of the circle. More generally, if an angle is θ radians, then for circle of radius R the arc length is $L = \theta R$. However, astronomers, like sailors, tend to speak in terms of degrees, arcminutes and arcseconds. Is is easiest to think of as dividing the circle in smaller and smaller parts:

1 degree (1°) is 1 circle/360
1 arcminute ($1'$) is $1^\circ/60$
1 arcsecond ($1''$) is $1'/60$

One arcminute is about the smallest angle you can resolve with the human eye. To put this into perspective, thats about the angular size a DVD would appear if held about 400 metres away. One arcsecond is the angular size you would get if you placed the same DVD 24 km away; its roughly the smallest angle you can resolve with a ground-based telescope. A space based telescope can resolve detail about ten times smaller than that - $0.1''$. If you held two DVDs next to each other at a distance of a hundred metres, then an observer, using her naked eye, could tell there were two separate DVDs; but at a distance of a km they couldn't. They would be blurred together. However, with a telescope you could tell there are two DVDs. This is nothing to do with magnifying the image; it is because telescopes give sharper images.

Fig. 1.2 shows how the sharpness of an image can make a dramatic difference. On the upper left hand side is a picture of a small portion of the Milky Way, taken with a camera on a large telescope in Hawaii. The "resolution" of the image is about $0.8''$, meaning that each star, which would ideally be an infinitesimally sharp spot, is blurred out to a blob of angular width about $0.8''$. On the upper right, the same image has been blurred to the resolution of the eye, about $1'$. Many stars are now overlapping, and you can't really tell whats going at all. Next, we see how useful going into space can be. On the lower left hand side, we see an image of a galaxy taken with the Hubble Space Telescope. On the lower right is the same galaxy as seen from the ground.

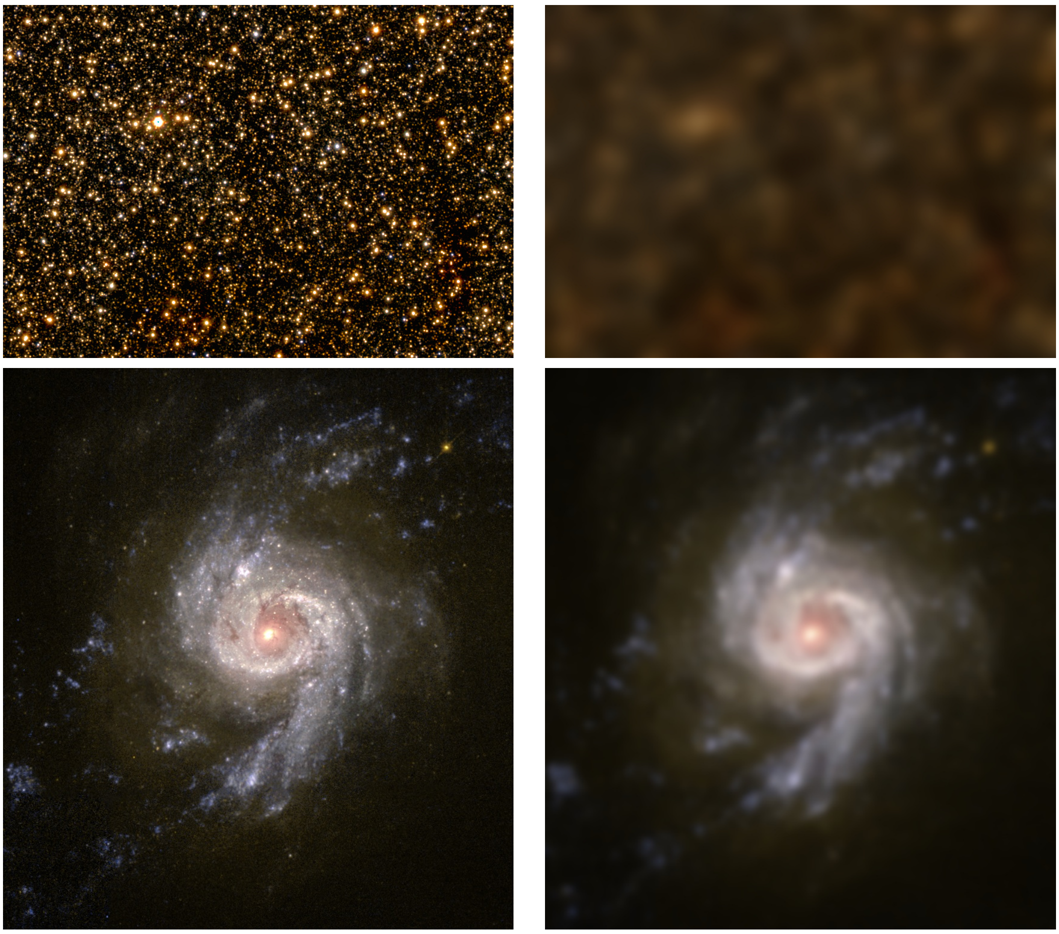


Figure 1.2: **Upper Left** *: A small patch of the Milky Way, imaged with the Wide Field Camera on UKIRT. This image has a resolution of about 0.8 arcseconds.* **Upper Right***: The same image, deliberately blurred in the computer to the resolution of the eye, 1 arcminute.* **Lower Left***: The galaxy NGC 3310, as imaged by the Hubble Space Telescope, with a resolution f 0.1 arcseconds.* **Lower Right***: The same image blurred to the resolution of a ground-based telescope, about 1 arcsecond.*

1.3.3 Extreme Temperatures

Detecting different kinds of light - infra-red, visible, UV, X-ray -requires quite different technologies, as we shall discuss in Chapter 4. But why do we get those very different kinds of light? Mostly, its because astronomical objects cover a huge range in temperature. In a comfortable room, it might perhaps be 20 degrees Celsius. Of course as Physicists we like to use the Kelvin scale of temperature, which gives temperatures above absolute zero. In Celsius terms, absolute zero is 273 degrees below zero degrees Celsius. In other words, that comfortable room temperature is 293 K, which is read as “two hundred and ninety three Kelvin”. That is fairly typical for a planet heated by its parent star; but other objects in the universe can be much colder or hotter; the coldest molecular clouds in the interstellar medium can be just 20 K; the surface of the Sun is at roughly 6000 K; and an accretion disc around a black hole could be 10,000,000 K.

Hot objects radiate light. If you take an object and heat it up, two things happen as it gets hotter. The first is that it emits *more* light. The second thing is that the light shifts towards shorter wavelengths, and so makes different types of light.

Our 20 K interstellar cloud will radiate at sub-mm wavelengths, similar to the radiation used by airport security scanners. To detect these waves we need radio dishes and receivers.

Our warm planet, at roughly 300 K, will emit light that peaks in the infra-red. This is also true of our bodies of course, which is how infrared cameras can see people in the dark.

The surface of the Sun, at 6000 K, emits regular visible wavelength light, that we can see with our eyes or with a CCD camera. Of course, in evolutionary terms, it is not a coincidence that this is the wavelength our eyes work best at.

The quasar accretion disc, at something like ten million degrees, will emit X-rays. To detect these X-rays we need to use X-ray detectors, and also need to go into space, because the X-rays are blocked by the atmosphere.

1.3.4 Big Numbers

Everybody knows that Astronomy is the science of big numbers - even in colloquial English, we will often talk about “astronomical numbers” if we mean something very big. The Milky Way has something like a hundred billion (10^{11}) stars in it, maybe four hundred billion. (Its quite tricky to estimate!) The number of galaxies in the observable universe is strangely similar - around a hundred billion. We can’t possibly meausre and catalogue every single one of those galaxies and stars individually, but in modern astronomy we do construct databases that are scarily big. The image you can see in Fig. 1.2 is a small section taken from a map of the whole Milky Way, stored on a database in Edinburgh and with about one billion objects in it.

What we do is to scan over such images, recognising each dot as a star or galaxy. For each of those objects, we measure various properties - position, brightness, shape etc - and then make a giant table, such as illustrated in Fig. 1.3. The challenge comes when you want to find the information on a specific star, or find a list of stars that satisfy certain criteria, and so on, from such a huge table. That processing is a serious computational challenge, which we will discuss further in Chapter 5.

1.3.5 Extreme Timescales

Most things in the Universe change very slowly compared to human lifetimes. The Universe as a whole has been evolving over billions of years and even the most massive stars, which burn through their fuel relatively quickly, last millions of years. However some things can happen fast. A supernova explosion can rise up within a few days and decay over weeks or months. A gamma-ray burst can happen in a few milli-seconds. A rock heading dangerously close to the Earth, by the time we spot it, can change its position radically in a few hours.

TOPCAT(1): Table Browser

Table Browser for 1: II_310-10m

	_r	_RAJ2000	_DEJ2000	Kmag	e_Kmag	ID	Epoch	cl	Ymag	e_Ymag	Jmag	e_Jmag	Hmag
1	0.16661	355.10187	-0.13184	17.902	0.149	41112074	2005.7629	1					
2	0.16465	355.1054	-0.12649	18.074	0.174	41112068	2005.7629	1					
3	0.16553	355.11411	-0.11991	16.877	0.059	41111656	2005.7629	1	19.397	0.118	18.462	0.102	17.69
4	0.16586	355.12072	-0.11374	17.595	0.112	41111631	2005.7629	1	19.877	0.181	18.844	0.145	18.407
5	0.1656	354.98184	-0.1646	18.082	0.178	42498152	2005.7629	1					
6	0.16199	354.99588	-0.16194	17.847	0.145	42498150	2005.7629	1					
7	0.16067	354.99564	-0.16061	18.577	0.282	42498147	2005.7629	1					
8	0.15574	354.99541	-0.15567			42497491	2005.7629	1	19.955	0.187			
9	0.15638	354.98335	-0.15549	17.273	0.086	42497490	2005.7629	1	19.638	0.14	19.091	0.194	18.022
10	0.16272	355.03966	-0.15781	17.291	0.088	42497498	2005.7629	-1	18.445	0.049	17.701	0.055	17.438
11	0.1631	355.04907	-0.15554	16.505	0.043	42497494	2005.7629	1	18.817	0.068	18.275	0.093	17.306
12	0.16485	355.05936	-0.15379	17.459	0.103	42497483	2005.7629	1	19.733	0.153			18.432
13	0.15965	355.05142	-0.15114	14.595	0.009	42497477	2005.7629	-1	16.067	0.008	15.45	0.008	14.896
14	0.15615	355.04072	-0.15075			42498021	2005.7628	1					19.035
15	0.15345	355.04617	-0.14634	18.444	0.253	42498137	2005.7629	1					
16	0.15636	355.0654	-0.14203			40859622	2005.7629	0	18.827	0.073			
17	0.16049	355.02167	-0.15902	15.048	0.012	42497505	2005.7629	-1	16.337	0.009	15.858	0.011	15.266
18	0.15464	355.00122	-0.15463	17.739	0.131	42497485	2005.7629	1	19.905	0.179			18.512
19	0.15429	355.01441	-0.15362	17.932	0.157	42497481	2005.7629	1	20.188	0.231			18.704
20	0.15281	354.99999	-0.15281	18.313	0.222	42498141	2005.7629	1					
21	0.15254	355.01279	-0.152	18.049	0.175	42498024	2005.7628	1					18.903
22	0.15145	355.00373	-0.1514	17.87	0.148	42498023	2005.7628	1					18.82
23	0.14996	355.00204	-0.14995	17.501	0.11	40860023	2005.7629	1					
24	0.14995	355.00204	-0.14994	17.489	0.105	42497470	2005.7629	1	19.751	0.155	19.261	0.227	18.318
25	0.15334	355.03222	-0.14992	18.041	0.175	42497469	2005.7629	1	19.573	0.133	18.85	0.156	18.353
26	0.15056	355.0242	-0.1486	16.232	0.035	40859861	2005.7628	-2					16.433
27	0.15053	355.02416	-0.14858	16.173	0.032	42497466	2005.7629	-1	17.266	0.018	16.883	0.027	16.264
28	0.14752	355.01483	-0.14677	16.966	0.065	42497464	2005.7629	1	19.389	0.112	18.896	0.163	17.861
29	0.1475	355.01489	-0.14675	17.13	0.079	40860019	2005.7629	1					
30	0.14196	355.00083	-0.14196	17.814	0.147	40860012	2005.7629	-1					
31	0.14195	355.00088	-0.14195	17.725	0.13	42498016	2005.7628	-2					18.53
32	0.13985	355.00911	-0.13955	15.104	0.013	40859619	2005.7629	-1	16.492	0.011	15.954	0.012	15.317
33	0.13983	355.0091	-0.13953	15.142	0.013	42498015	2005.7628	-2					15.415
34	0.14439	355.04665	-0.13665	17.566	0.118	40859857	2005.7628	1					18.253
35	0.139	355.02791	-0.13617	14.097	0.006	40859618	2005.7629	-1	15.375	0.005	14.883	0.005	14.28
36	0.14116	355.04785	-0.1328	17.443	0.106	40860008	2005.7629	1					
37	0.13652	355.03311	-0.13244			40859609	2005.7629	0	16.251	0.009			
38	0.13912	355.04726	-0.13085	17.913	0.162	40860007	2005.7629	1					
39	0.14174	355.05495	-0.13065	16.142	0.033	40859606	2005.7629	1	18.34	0.048	17.757	0.058	16.857
40	0.12728	355.02078	-0.12557	17.253	0.088	40859853	2005.7628	1					18.51

Figure 1.3: *Example of a table of numbers derived from an astronomical image. Each row represents one object, with the columns holding the measured properties of those objects. Real life tables can be hundreds of millions of rows.*

Things that happen fast are becoming increasingly important in modern astronomy. Dealing with these transient events poses some tricky challenges - not just technical challenges, but also organisational challenges, and social challenges. How do we share out telescope time to deal with events that don't fit neatly into whole nights? How do we respond to alerts that come to us over the internet?

1.4 The Horse and the Cart

It's only thanks to major advances in technology that we've gained so much understanding of the Universe around us. We'll find in each chapter, that the technology is at the core each major astronomical discovery that we explore. Astronomy also drives technology though, so which is the horse and which is the cart? Who is pulling who?

Let's take an every day example of connecting to the internet using wi-fi. That is possible thanks to the work of Radio Astronomers. They were looking for radio pulses from black holes and needed to exchange the large quantities of data that they were analysing in a wireless way. The result of that research innovation is wi-fi technology, a case of Astronomy driving the technology.

Astronomers have a habit of being the first to use and exploit new technology though. Cases of technology driving astronomy, include astronomers becoming some of the very first users of the worldwide web and the CCD technology that you now have in your digital camera. Astronomers were the first non-military users of infrared cameras which, in their first test runs at the telescope discovered a previously unseen population of very cool stars. Astronomers also benefited from the military innovation of three-axis stabilized spacecraft, central to the future of space-based X-ray observatories.

Science and technology have always been intimately tied together and they always will be. But there is a third factor to also consider which is commercialisation and manufacturing. CCDs, when first invented were incredibly expensive, severely limiting the size of the camera that the

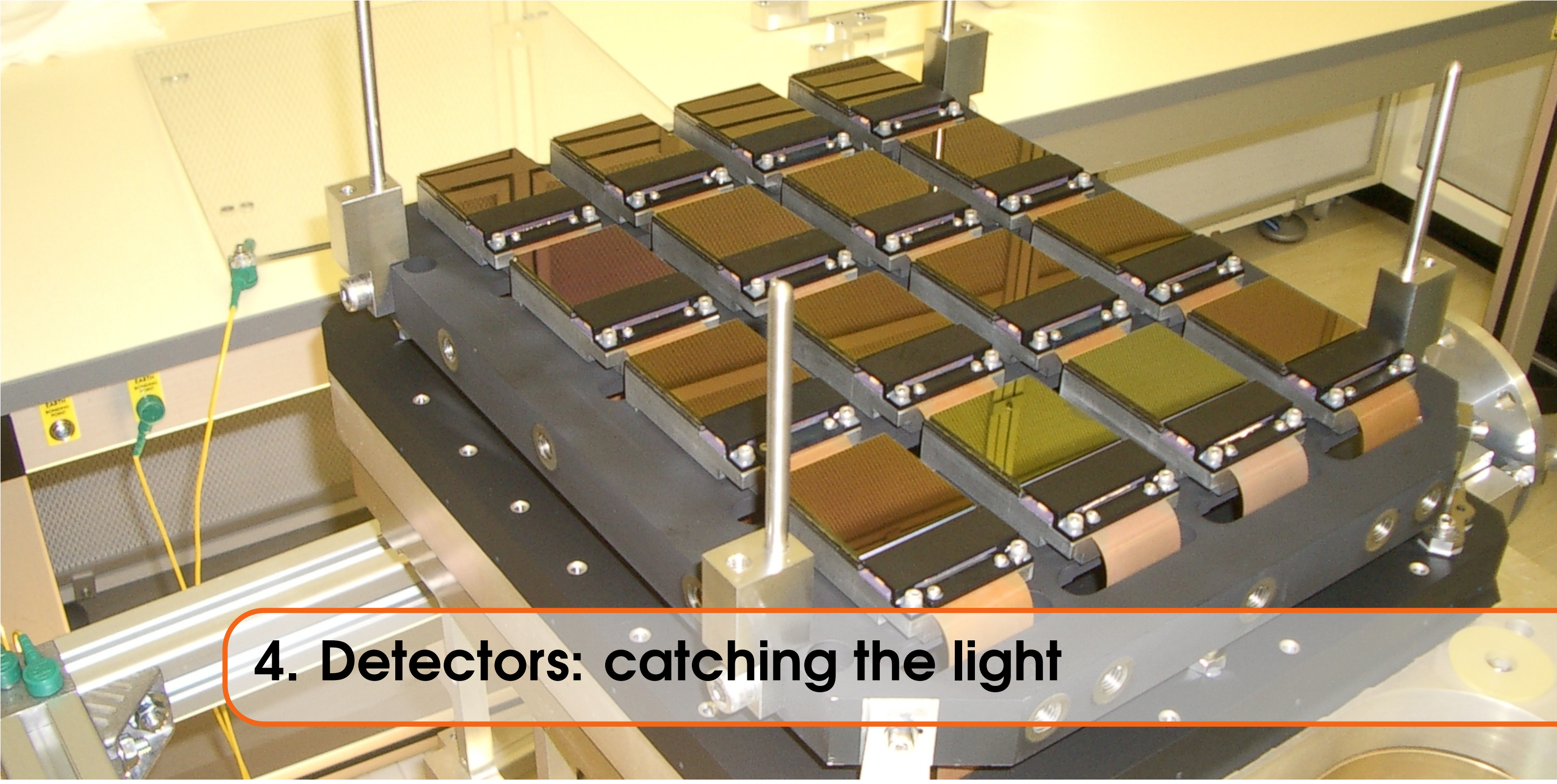
Astronomers could afford to build. Now, however, with their prevalence in smart phones, webcams and digital cameras, CCDs are very affordable, and the cost of the camera is no longer a limitation for the optical technology of the future. Nearly all forms of Astronomical observations would benefit from the observatory being launched into space. This is currently prohibitively expensive, though, for all but the top-rated missions selected by the International Space Agencies around the world. Potentially this could all change in the future if there was a commercial benefit for space travel. Perhaps mining asteroids for precious metals will be the commercial horse that permits the technology and science cart to travel into space.

1.5 Test your understanding

1.6 Further reading

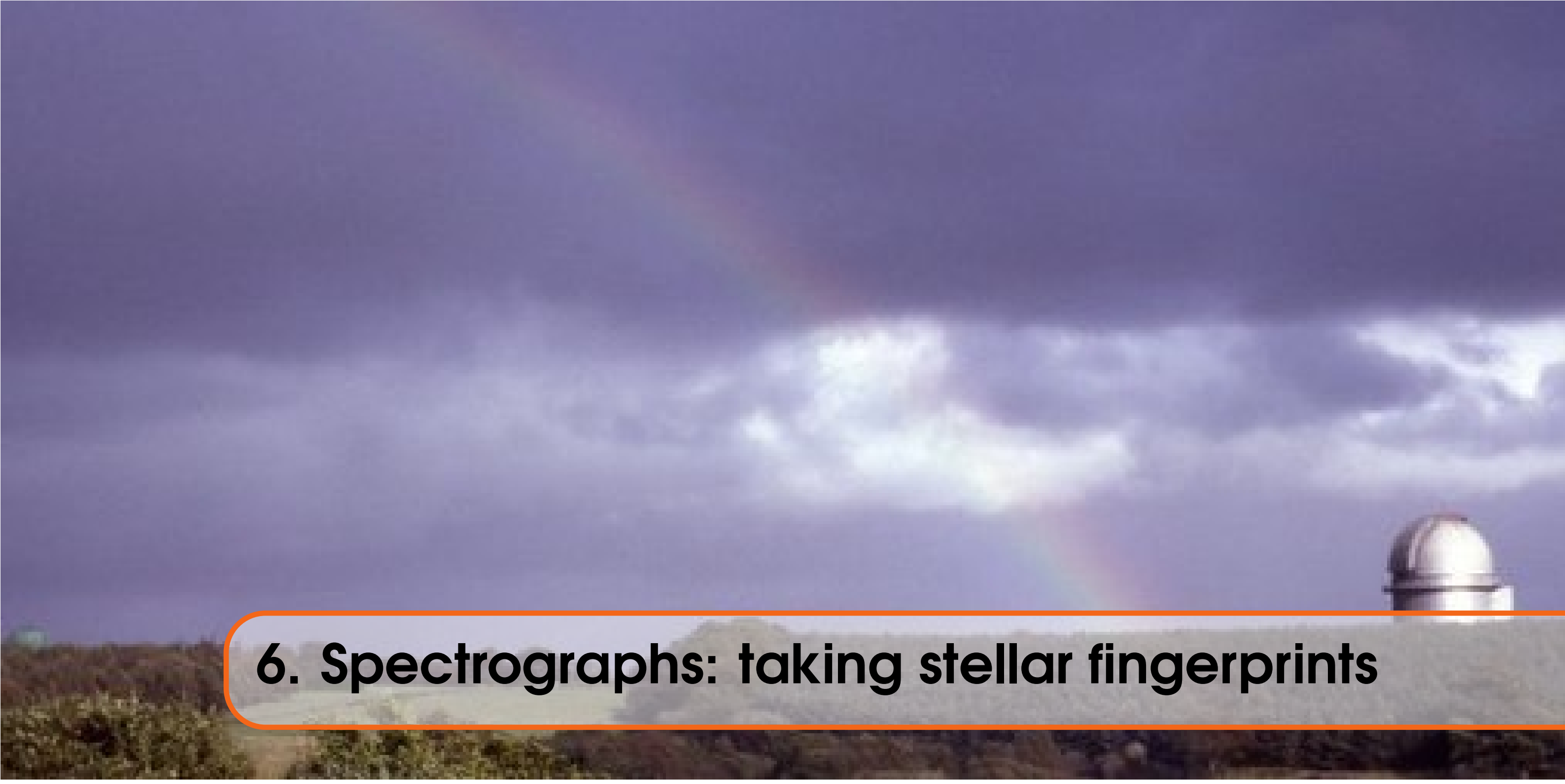
2. Telescopes: Picturing the Universe

3. Space: Getting above it all



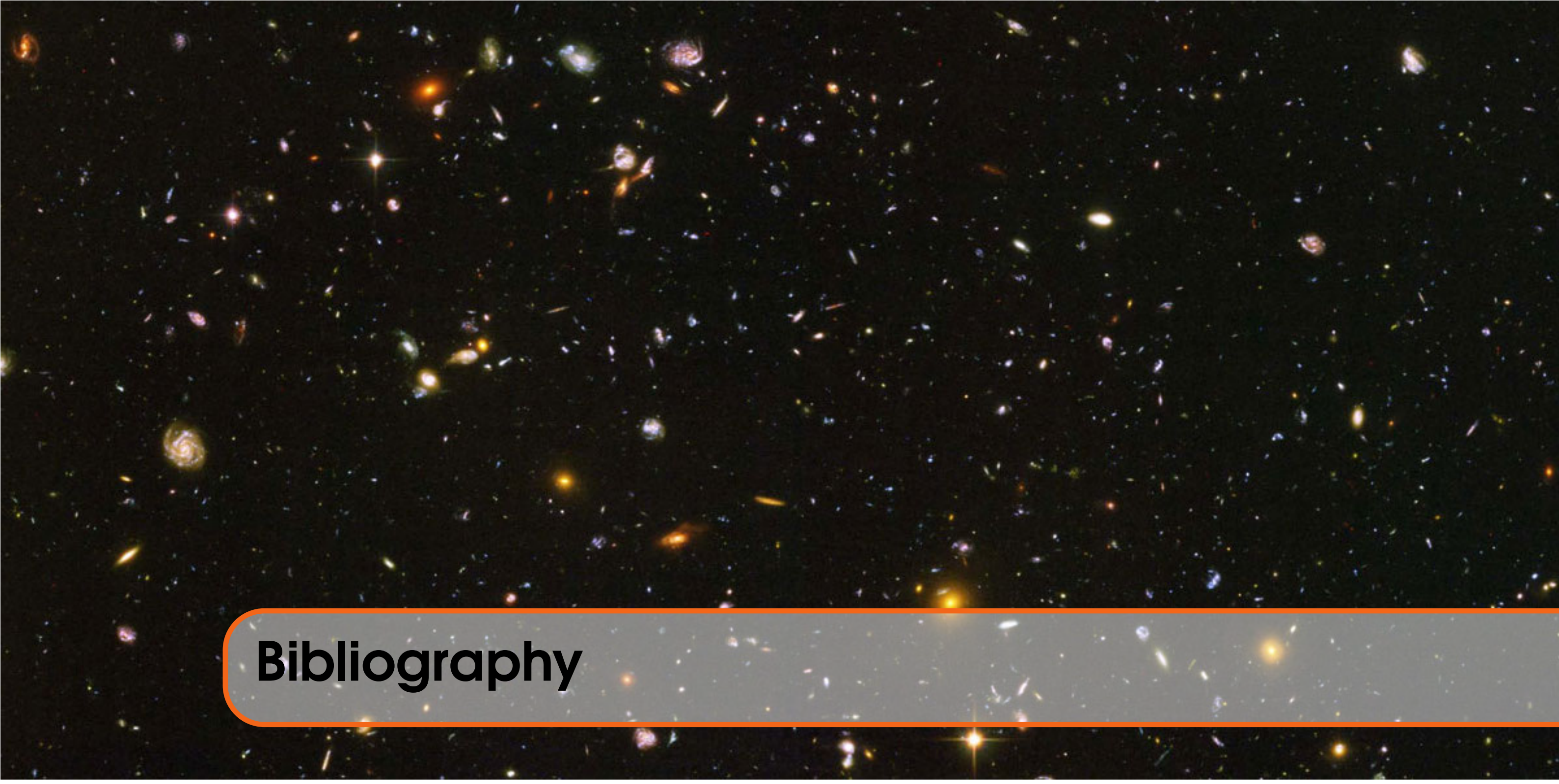
4. Detectors: catching the light

5. Computers: crunching the data



6. Spectrographs: taking stellar fingerprints

7. Closing thoughts



Bibliography

Glossary

Glossary

Angular Resolution The smallest angle you can separate, with a particular optical system - human eye, big telescope, etc.. 13

Boondoggle TA trip to a conference in Tahiti that isn't strictly speaking essential for your research.. 13

Exercise Solutions

Picture credits