Development of the Telescope

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SCIE1121: Our Universe
University of Western Australia
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Expected Learning Outcomes

After this lecture you should have an understanding of the conventions astronomers use to describe the locations of objects in the sky, of the development of the telescope, and you should be able to compare and contrast reflector vs refractor telescopes for optical astronomy, and describe how radio telescopes work.

Assessed Content:

- Describe astronomical coordinate systems.
- Describe pre-telescope observing instruments and explain how the Sun, Moon and Earth were measured.
- Explain the engineering requirements that make a more 'powerful' telescope.
- Describe optical telescopes, explain the differences between refractive and reflective telescopes and the advantages and disadvantages of different detectors.
- Describe radio telescopes and explain the advantages and disadvantages of aperture synthesis.

TEXTBOOK REFERENCE: Openstax Astronomy

1 Astronomy before the telescope

Ancient astronomy as part of culture and mythology has already been discussed in other lectures. Here, we will explore the development of astronomy as a science.

1.1 Observations

Without telescopes and a method of recording and analysing what you see through them (photography) there are only three qualities of celestial objects that can be observed:

- Position — relative to the 'fixed' stars
- Brightness
- Colour — only for some objects (e.g. the Moon, Mars, Betelgeuse, Rigel)

Brightness was difficult to estimate by eye (can only estimate relative to other objects nearby), and only a handful of objects had significant colour. Position, on the other hand, could be measured accurately using simple tools to measure the angle between celestial objects, or between the object and the horizon.

Intelligent observations using simple tools allowed the astronomers of antiquity to make incredible discoveries about the Universe.

1.2 Coordinate Systems

Cartesian coordinates (x, y, z coordinates) are not practical for describing the position of celestial objects given the uncertainty in the distances involved (and which the ancient astronomers had no way of knowing). On Earth (a sphere) we measure our position in terms of two angle-based coordinates, latitude and longitude. For example, Perth is located 31.95 deg S, 115.86 deg E (meaning 31.95 deg South of the equator and 115.86 deg East of the Greenwich Meridian).

Since, from the point of view of astronomers and telescopes on Earth, the sky appears to form a hollow sphere around the Earth, it is convenient to translate this spherical coordinate system onto the sky. The position

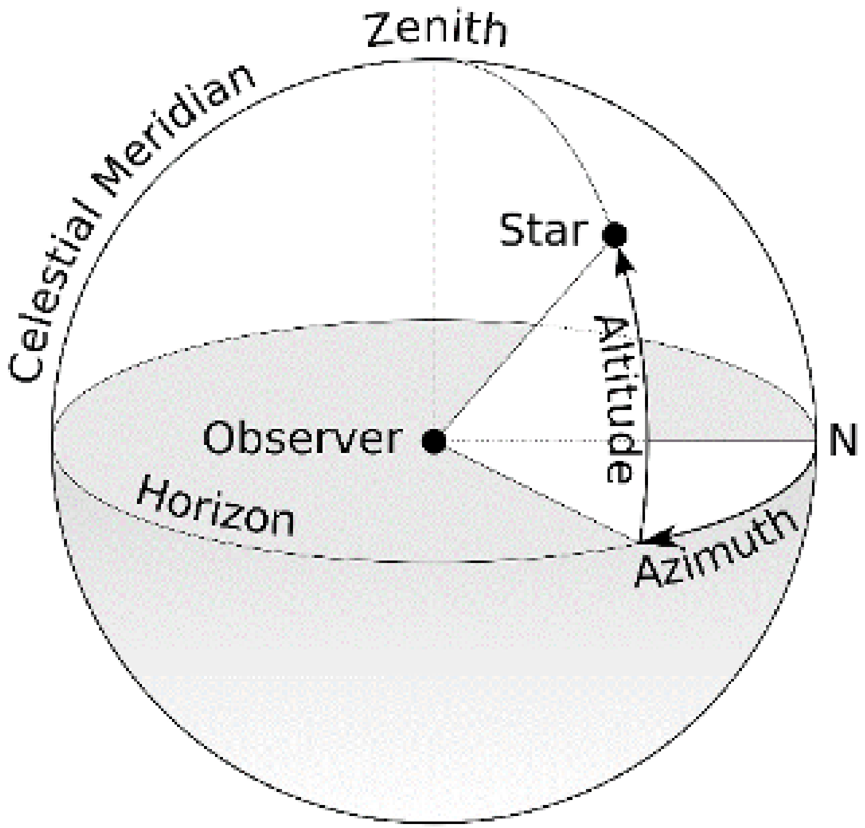

Figure 1: One example of an astronomical coordinate system using altitude (angle above horizon) and azimuth (angle relative to a reference direction, e.g North, 'around' the horizon). The point directly overhead is called the 'zenith' and the angle directly below is called the 'nadir'. Alt-az coordinates depend on the location of the observer. These days alt-az coordinates are still used: fixed ra-dec coordinates are often converted to Alt-az by computer systems that drive professional telescopes.

of objects in the sky is then given by two angles.

Ancient astronomers measured the position of celestial objects using altitude (angle above the horizon) and azimuth (the compass bearing). This is very easy to do, but since the Earth is turning (or, as the ancients believed, the sky is turning) this coordinate system is only valid for a particular instant of time.

To make the coordinate system valid at any time, we need consistent (fixed, unchanging) reference points (such as the equator and Greenwich Meridian used in latitude/longitude). The coordinate system modern astronomers use is called equatorial coordinates, and the two angles are called Right Ascension and Declination.

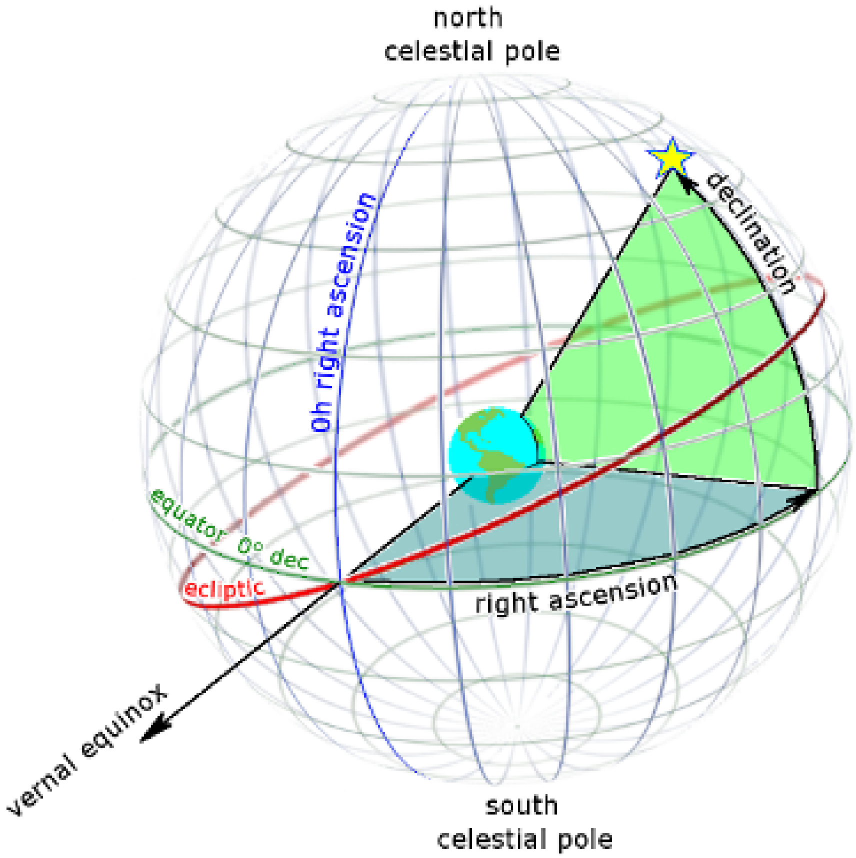

Figure 2: The Right Ascension and Declination (ra-dec) coordinate system used by modern astronomers. Declination is the angle between the projection of the equator on the celestial spehere and the object. Right ascension is analogous to longitude, relative to a position agreed upon by astronomical convention.

Declination of an object is the angle above or below the celestial equator (the line in the sky directly above the Earth's equator). The declination is given in degrees from $+90$ deg (the point directly above the Earth's North Pole, also known as the North Celestial Pole) to -90 deg (the South celestial pole, the point directly above the South pole).

Right Ascension is similar to longitude. The zero-point is arbitrary but is agreed on by astronomers. The zero-point is the north-south running line in the sky that is directly overhead at noon on the Vernal Equinox (21st March). As a result, the angle is given in hours, minutes and seconds (an object with a right ascension of 1 hr will be overhead at 1pm on 21st March). This point is sometimes referred to as the 'first point of Aries'.

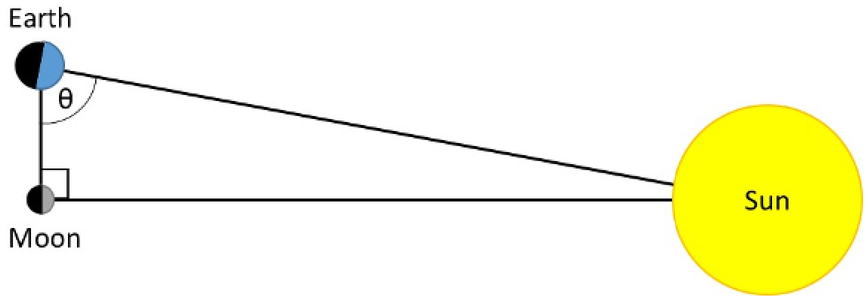

Figure 3: Method used by Greek astronomer Aristarchus to measure the distance to the Sun and the Moon using trigonometry and the properties of the right-angled triangle formed between the Earth, Moon and Sun.

2 Ancient Greek astronomy: triangles all the way down

Modern astronomy could be said to have begun around 600 BC with the ancient Greeks, who built on the knowledge of the Egyptians and other middle-eastern cultures. The Greeks realized that the Earth is a sphere. They observed that the altitude of the pole star (Polaris) got higher the further north you were. They also noticed that, during a lunar eclipse, as the shadow of the Earth passed over the Moon, it always formed part of a circle, regardless of what angle the shadow was cast from. From these, and other observations, they reasoned that the Earth must be spherical.

2.1 Aristarchus — measuring the Sun and the Moon

Around 270 BC the Greek astronomer Aristarchus attempted to measure the distances to the Sun and the Moon. When the Moon is exactly half illuminated as seen from Earth, it forms a right-angle with the Earth and the Sun. Aristarchus attempted to measure the angle θ between the Moon and the Sun.

Aristarchus worked out that the distance from the Earth to the Sun is 19 times the distance of the Earth to the Moon. In reality, the Sun is around 400 times further away than the Moon. The error possibly arose due the difficulty of determining when the Moon is exactly half illuminated with the unaided human eye. However, Aristarchus was at least on the right track.

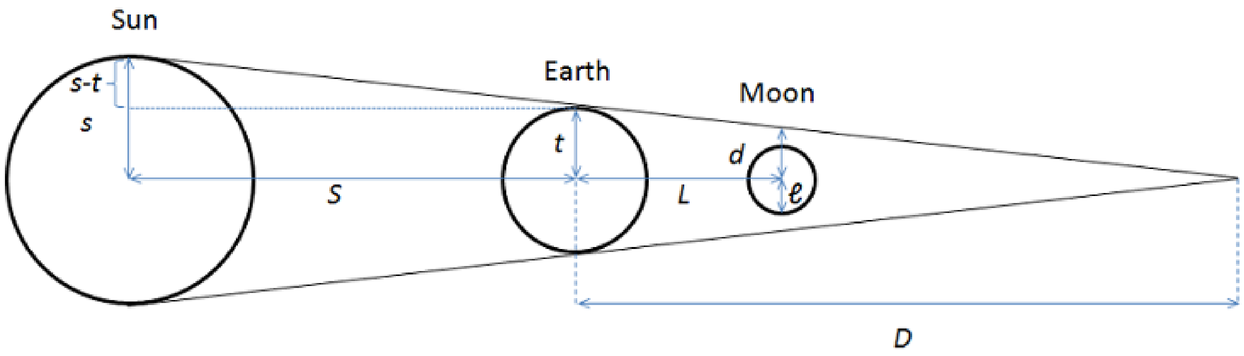

Figure 4: How Aristarchus went about calculating the relative sizes of the Earth, Moon and Sun, measuring the relative size of the Moon and Sun in the sky and the size of the Earth's shadow cast on the Moon.

Aristarchus also tried to measure the relative sizes of the Sun, Moon and Earth using the shadow of the Earth on the Moon during a lunar eclipse. Since the Sun and the Moon are the same size in the sky, the Sun must be larger than the Moon in proportion to their distances from Earth (19 times larger by his measurement, 400 times by ours). Aristarchus estimated the diameter of the Earth's shadow on the Moon to be 2.7 times larger than the diameter of the Moon. From this measurement, and simple geometry, the relative size of the Earth could be calculated.

Aristarchus' method was correct, but his calculated values were wildly incorrect due to the errors introduced by trying to judge shadows on the Moon using the unaided human eye. Aristarchus was a proponent of the heliocentric model of the Solar System, but his views were ignored in preference of Aristotle's geocentric model.

2.2 Eratosthenes — measuring the Earth

Thanks to the work of Aristarchus, the ancient Greeks now had the distances and sizes of the Sun and the Moon in terms of the Earth's diameter (though their values were very wrong). In around 240 BC, Eratosthenes worked out a way to measure the diameter of the Earth.

Eratosthenes received word that at noon on the summer solstice (21st June in the northern hemisphere) the Sun shone vertically down a well in the town of Syene (also called Swenet or Aswan). That is, the Sun was directly overhead at that time on that day. This is because Syene is on

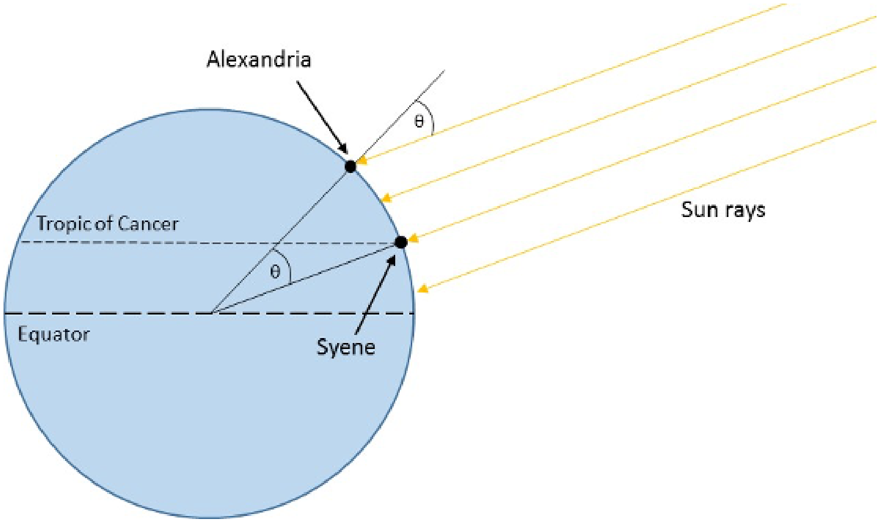

Figure 5: Eratosthenes' measurements to deduce the diameter of the Earth - measuring the angle of the sun at different places on Earth's surface. This measurement uses the properties of similar triangles, proving there is a use for the geometry you learn in high school.

the Tropic of Cancer.

Eratosthenes then measured the angle of the Sun above his home city of Alexandria (north of Syene) at noon on the summer solstice (he found the angle of the Sun to be around 7deg below the zenith). By knowing how much further north Alexandria is than Syene, and assuming that the Earth is a sphere, Eratosthenes calculated the circumference of the Earth to be around 40,000 km, in very good agreement with our modern measurement.

2.3 Hipparchus — precession and magnitudes

Hipparchus made accurate observations of the apparent motions of the Sun, Moon, planets and 850 stars using simple sighting instruments. He discovered precession, a systematic shift of the position of stars over time. Today, we know this is due to slow changes in the alignment of Earth's axis of rotation.

Hipparchus also introduced a system of measuring the brightness of stars that, in a modified form, is still used today. Hipparchus classified stars in to six brightness categories. The brightest stars were called first magnitude, while sixth magnitude stars are the faintest visible to the human eye.

In this system, brighter objects have smaller magnitudes. The Sun has a magnitude of -26.7 and Venus a magnitude of -4.9. Neptune, with a magnitude of -7.8, is not visible to the human eye. Today, a difference of one magnitude is equivalent to a difference in brightness of a factor of around 2.5 (magnitude is a logarithmic scale).

2.4 Ptolemy and Copernicus

We have already mentioned in a previous lecture how Ptolemy, the last of the great ancient Greek astronomers (circa 100-178 AD), proposed a complex series of epicycles, to account for movements of the planets that could not be explained by Aristotle's geocentric model of the Universe. Our narrative then jumps to Nicolaus Copernicus (1473-1543), who proposed a heliocentric model, but retained the circular orbits and complex epicycles favoured by the ancient Greeks.

3 The European Enlightenment Era

3.1 Brahe and Kepler

Tycho Brahe is regarded by many as the greatest of the pre-telescope astronomers. He made highly accurate measurements of the motion of the planets and accrued a huge wealth of data over 20 years of observations. He also measured the length of a year to within one second using sighting instruments larger and more accurate than any that had come before.

Brahe was a colorful and somewhat infamous character, famous for challenging other scientists to duels over various scientific and mathematical theories. During one eventful duel (conducted outdoors at night in darkness), Brahe had his nose sliced off. For the rest of his life he wore a silver prosthetic nose. Upon his death, he left the records of his observation to his assistant Johannes Kepler, who, as we have discussed in a previous lecture, used Tycho's observations to prove the heliocentric model of the Universe.

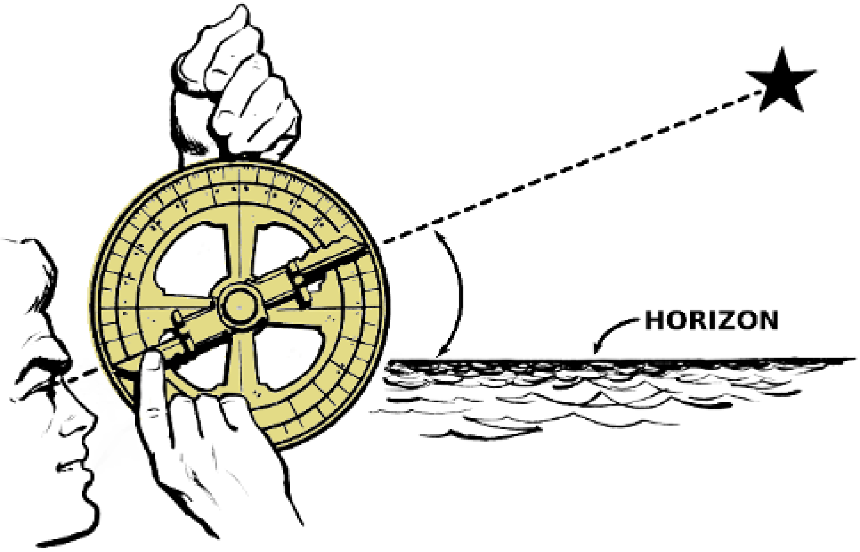

Figure 6: Example of an astrolabe being used. Even to this day, all ships carry an astrolabe and most individuals working on the bridge of both merchant and navy ships are capable of navigating by the stars using an astrolabe, in case a ship is left without working GPS navigation systems.

4 Pre-telescope astronomical instruments

Before the invention of the telescope, astronomers used simple sighting instruments to make their observations of the positions of celestial bodies.

Astrolabe — in its simplest form, an astrolabe consisted of a disc with a sight that could be pivoted to measure the altitude of an object. Astrolabes showing the altitudes of various bright objects (stars and planets) at different times were used to tell the time.

Quadrant - quadrants were graduated quarter-circles used to measure the altitude of celestial objects. Mural quadrants were mounted or painted onto a wall. The wall was aligned with a meridian (aligned north-south). Only objects passing overhead (transiting) could be viewed and measured. The transits of stars were the most accurate way to tell the time until the development of atomic clocks in the 20th century. Mt Stromlo Observatory in Canberra (now part of the Australian National University) was responsible for the official timekeeping of Australia until the mid-20th century through the facility being able to perform highly accurate transit timing.

Antikythera mechanism — while not used to make measurements of

Figure 7: A wall-mounted mural quadrant. Until atomic clocks were commonplace, the use of a quadrant to time transits of stars across the meridian was the most accurate method of timekeeping.

the stars, the Antikythera mechanism is a fascinating astronomical device. It is essentially a mechanical computer used to predict astronomical events such as eclipses. It is a highly complex device and has been dated to between 200 and 100 BC. The knowledge of these advanced devices was somehow lost in antiquity.

5 Telescope sensitivity and resolution

The 'power' of a telescope is a combination of its sensitivity and angular resolution.

The sensitivity of a telescope is determined by its collecting area and the sensitivity of the detector receiving the image. Telescopes with a larger diameter lens or reflector have a greater collecting area and so direct more photons to the detector (our eye, or a camera) and so have a greater sensitivity.

Angular resolution describes the ability of any image forming device (e.g. a telescope, a camera, or our eye) to distinguish small details of the object being viewed. The human eye has an angular resolution of about 1 arcminute. This is equivalent to being able to distinguish two objects

Figure 8: A 2007 reproduction of the Antikythera mechanism, an ancient device for predicting eclipses and other astronomical events.

separated by roughly 30 cm at a distance of 1 km away.

Angular resolution can be calculated using:

$$\theta = 1.22\frac{\lambda}{D}$$

Where θ is the angular resolution in radians, λ is the wavelength of the radiation (light), and D is the diameter of the lens or reflector.

So, telescopes with a larger diameter lens or mirror are both more sensitive and capable of distinguishing finer detail in an image. For these reasons, the larger a telescope is in diameter, the more ‘powerful’ it is. Astronomers are always trying to build bigger, more powerful telescopes that can distinguish fainter objects further away.

5.1 NOT ASSESSED - Some information for prospective telescope buyers

Often amateur astronomers are seduced by telescopes offering high magnifications (i.e. making an image of something that looks bigger). If you are tempted to buy a telescope, remember it is the diameter of the telescope that determines the quality of the image you will see through it, and how much detail you will see of faint objects. A good telescope for beginners is a reflector telescope with a 5-6 inch diameter mirror on a ‘dobsonian’ mount, and will set you back $800 - $1000.

If you are interested in purchasing a telescope for hobby astronomy, I strongly recommend getting involved in a local astronomical society. These societies are filled with folks who are very knowledgeable about telescopes and will often have nights where you can visit and use a variety of scopes to see what you like or will find useful, for free or a small cost. They offer education nights where you can listen to experts too, and they can teach you how to get the most out of a telescope before you purchase. Some will also sell their telescopes through these societies, so you may even bag a deal from somebody ready to upgrade their scope.

Whatever you do: do not purchase the small scopes you may see being sold at Australian Geographic or museum stores. They promise great things on the box but I have seen too many people sorely disappointed (particularly children), and even put off amateur astronomy by these cheap scopes. You can access many excellent telescopes (some with comparable diameters to small professional telescopes) through the local astronomical society for less money. More and more young people are attending these society nights, so don’t be afraid to go along and find out more.

6 The development of optical telescopes

The first optical telescope was invented in 1608 by Hans Lippershey, a German spectacle maker. Thanks to his skill as a spectacle maker, Lippershey was able to construct a device that used glass lenses to refract light and magnify the image of a distant object. Telescopes that use lenses are called refractive telescopes.

Galileo received word of Lippershey’s invention, and based on his own understanding of optics and the description he had been given, built his own telescope. Galileo improved on Lippershey’s design and made a fortune selling telescopes, which he used to finance his own research.

Galileo’s telescope design is called a Galilean telescope. Galileo was not the first person to build a telescope, but he was the first to point

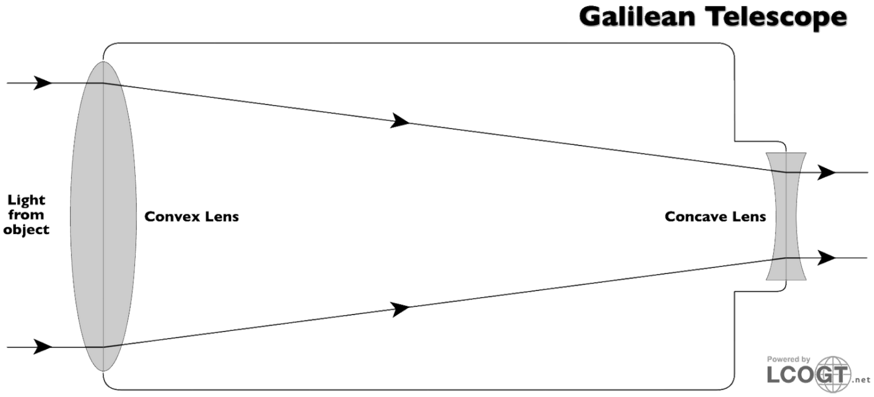

Figure 9: The main optical components in a Gallilean telescope: a convex lens and concave lens focus light.

a telescope at the night sky. Galileo saw craters and mountains on the Moon and made detailed drawings of these features. He saw that Mercury and Venus had phases like the Moon, which explained why they varied in brightness over the course of the year and was evidence of the fact that they are interior planets (they orbit between the Sun and the Earth). Galileo observed that Saturn has “ears”. These were the rings of Saturn. Galileo’s telescope was not powerful enough to see that they were rings around the planet. Galileo also observed four points of light that moved back and forth across the disk of Jupiter. Over days and weeks he noticed that these points of light moved with perfect regularity. He concluded that they were moons orbiting Jupiter. This was the first evidence of objects that were definitely orbiting a body other than the Earth and helped to disprove the geocentric view of the Universe. Today, these four largest moons of Jupiter are called the Galilean Moons.

Kepler improved Galileo’s telescope design still further. Keplerian telescopes produce greater magnification than Galilean telescopes though the image is upside-down.

Refractive telescopes have some key problems. One is that glass (or any other type of lens) absorbs some of the light, making it difficult to see dim objects. Another major problem with refractive telescopes is chromatic aberration.

Different colours of light have different wavelengths. Different wavelengths of light refract by a different amount through the lenses of the telescope (or through any medium. This is why a prism splits white light into a rainbow of colours).

Through the lenses of a telescope, chromatic aberration causes images to become blurry, since the different colours focus at different points.

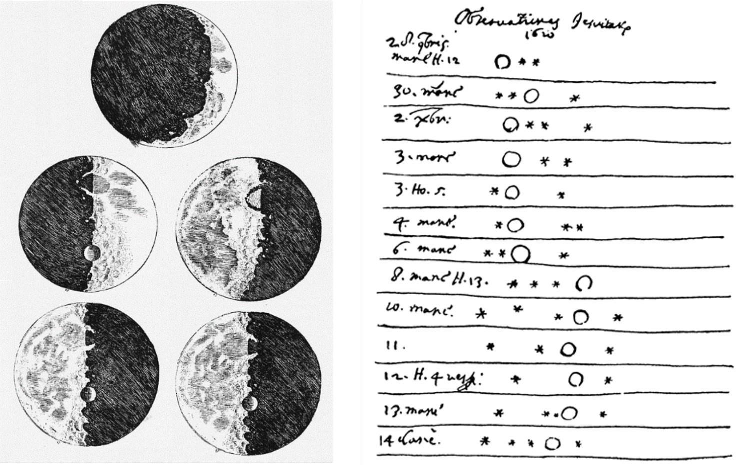

Figure 10: L: Gallileo's sketches of the phases of the Moon and the craters on the moon. R: Observations of the four moons of Jupiter visible through a telescope, first observed by Gallileo.

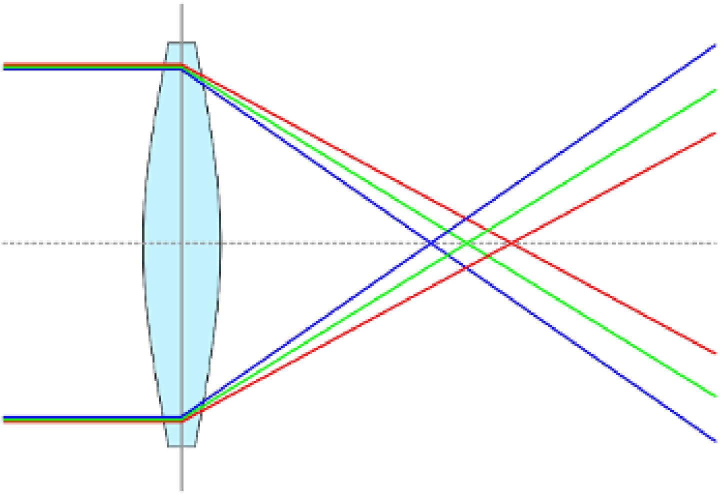

Figure 11: Chromatic aberration: light of different wavelengths refracts at slightly different angles through a lens, resulting in different colors focussing at slightly different positions. Chromatic aberration can be seen as a colored haze or ring around an object viewed through a refractor telescope.

Astronomers first tried to solve this problem by making lenses that only refracted the light through a very small angle, reducing the noticeable effects of the aberration. However, this required the telescopes to be incredibly long and unwieldy. Later achromatic lenses were developed that greatly reduce the effects of chromatic aberration.

6.1 NOT ASSESSED: Australian refractor telescopes

Figure 12: The Yale-Columbia refractor telescope at Mt Stromlo Observatory before the 2003 bushfires that destroyed the observatory, including this telescope.

One of the last refractor telescopes used by professional astronomers was the Yale-Columbia 26 inch refractor (a 26 inch primary lens) at Mt Stromlo Observatory in Canberra. The telescope was used to investigate the distances and movements of southern stars by measuring their parallax (angular movement) over six month intervals.

The refractor assisted the planning of NASA's Voyager missions to the outer planets by taking photographs of the moons of Jupiter and Saturn. From 1977 to 1992, the telescope was used by the University of Virginia to extend its parallax program to the Southern Hemisphere.

Housed in a dome with a roof made of aluminium, the telescope was destroyed in the 2003 Canberra firestorm. The heat of the fire was so fierce that the aluminium roof burned brightly, visible through the thick black smoke. Some witnesses compared it to being as bright as the sun rising. The outer walls of the telescope and the concrete equatorial mount survived and still stands as a reminder of the 2003 bushfires at the Observatory. If you visit and look closely, you can see fragments of the melted aluminium roof still on the concrete.

7 Reflector Telescopes

The problems of absorption and aberration were solved by Isaac Newton, who developed the reflective telescope. Reflective telescopes use a curved mirror to focus light rather than a lens. Although no mirror reflects 100% of the light hitting it, the amount of light reflected is significantly greater than the amount transmitted through a lens. Mirrors do not cause chromatic aberration of the light reflecting from them, and so you get a sharper, brighter image.

Large reflecting telescopes can be made more easily, and give a better image, than refractive telescopes. In 1845 William Parsons had a reflecting telescope built with a 1.8 m diameter mirror made of speculum (a copper/tin alloy that tarnished easily but made a good mirror when polished). This remained the largest telescope in the world until 1917 when a 2.5 m diameter telescope was built in America.

The largest, single optical telescope at the time of writing is the 10.4 m diameter GTC telescope in the Canary Islands. Australia's largest optical telescope is the 4m Anglo-Australian telescope, at Siding Spring Observatory in New South Wales.

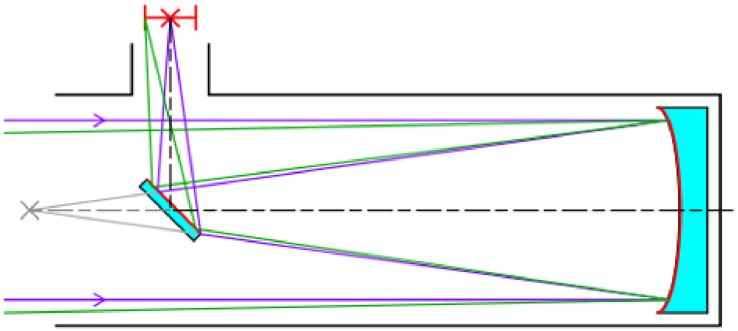

Figure 13: A Newtonian telescope uses mirrors to focus light instead of lenses. Almost all telescopes used by professional astronomers are Newtonian reflector telescopes.

8 Atmospheric limitations

Although telescopes with larger diameter mirrors should be able to distinguish finer detail, turbulence in the atmosphere, which refracts light and causes stars to twinkle, places a limit on the actual angular resolution of ground-based telescopes. This, and the absorption of light by the atmosphere, are the reasons for space-based telescopes such as the Hubble Space Telescope (HST). Although the HST only has a 2.4 m diameter primary mirror, it produces images with greater resolution than any other telescope because it is up above the atmosphere.

Building larger ground-based telescopes only improves their sensitivity, not their image resolution. Recently, adaptive optics have been used to improve the resolution of ground-based telescopes. A "guide star", which can be an actual star or a laser beam, is used to measure the distortions produced by the atmosphere above the telescope. The telescope's mirror is then deformed to compensate for the atmospheric distortion.

9 Photography

When you imagine what astronomers may spend their time doing, people usually imagine us looking directly through telescope eyepieces (usually smoking a pipe, thanks to a very famous photo of Edwin Hubble). However, most of modern astronomy involves using computers to control the telescope and control cameras that will capture greater detail than we could hope to directly see through an eyepiece of even a large telescope.

Before the invention of photography, astronomers did have to draw what they could see through a telescope eyepiece. This made precise measurement difficult and observations subjective. The arrival of practical photography revolutionized astronomy.

Long-exposure photographs meant objects too faint to be seen by eye could be observed. The photographic plates also made a permanent record that could be used for later study. The photographs enabled precise measurements to be made of the position of stars and other features in the image (this was tedious work, mostly performed by female "computers", whose ground-breaking work we'll visit again in later lectures). Hundreds

Figure 14: When you imagine an astronomer, do you picture them with a pipe? It's probably because this photo of Edwin Hubble is fairly ingrained in our collective consciousness. You're more likely to find modern astronomers slouched behind their computers with a large cup of coffee. If you look closely at this photo, you will also see that Hubble isn't actually looking through this very large telescope - he's looking through the finder scope!

of thousands of stars were catalogued in this way.

One limitation of photography was that the reaction of the photographic film to light was highly non-linear. This means that a star that was twice as bright as another did not produce a spot on the photograph that was twice as dark (photographic film darkened when exposed to light). Objective measurements of the brightness of stars were extremely difficult to perform.

9.1 Photomultipliers

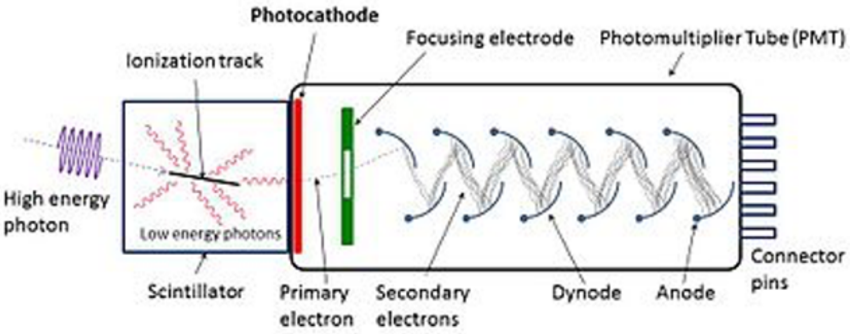

Figure 15: A photomultiplier tube converts incoming photons into a cascade of electrons, amplifying the signal so it can be read by a detector.

Photomultiplier tubes (PMTs) were invented in the 1930 and allowed precise measurements of brightness to be made. In a PMT, an incoming photon is absorbed by the scintillator crystal which releases an electron. This electron is accelerated down the PMT by an electric potential which causes it to gain energy. Each time an electron strikes an electrode it produces a shower of further electrons. This pulse of electrons is detected at the end of the PMT. In a PMT, a single photon produces a known amount of electrical current. The output of the PMT is linearly related to the number of photons coming in and so accurate brightness measurements can be made.

Although these PMTs had a linear response and were sensitive to a wider range of frequencies (colours) of light than photographic film, constructing a full image using them would be an extremely tedious process.

9.2 CCD detectors

Modern optical telescopes use charge-coupled devices (CCDs). In a CCD individual pixels are constructed of semi-conductor material. When a photon strikes the semi-conductor it is converted to an electron resulting in an electric charge in the pixel. This means that a long exposure can be used to image faint objects because the stored charge in the pixel increases with each photon that is absorbed. The charge built up in each pixel is read out by a “shift-register”.

Like PMTs, CCDs have a linear response to incoming photons, but they build up a full image of the observed object, just like photographic film. Another advantage of CCDs is that the image they take can be directly digitized, emailed anywhere in the world, and analysed using image processing software, with much of the tedious work being automated by computers.

The camera in your phone was developed using the same technology that originated for use in astronomy.

10 The development of radio telescopes

Radio astronomy did not exist until the 20th century. This is because humans are not sensitive to radio waves and the practice of radio astronomy had to wait until we had developed radio receivers sufficiently advanced to detect signals from space. Even then, astronomers were slow to adopt the new technology because stars do not emit significant amounts of radiation at radio frequencies.

The earliest example of radio astronomy is from 1932. Karl Jansky, an engineer at the Bell Telephone Company was assigned the task of determining what was causing interference in radio transmissions at a frequency of 20.5 MHz. Jansky realized that the intensity of the interference varied with a period equal to the length of a sidereal day (23 h 56 m) and that the interference signal was strongest when the galactic centre was over head. Jansky reported his discovery but was assigned to other projects and was not able to carry on the work he had started.

Inspired by Jansky’s work, Grote Reber, a professional radio engineer, tried to get a job as a radio astronomer but was turned down. At the time,

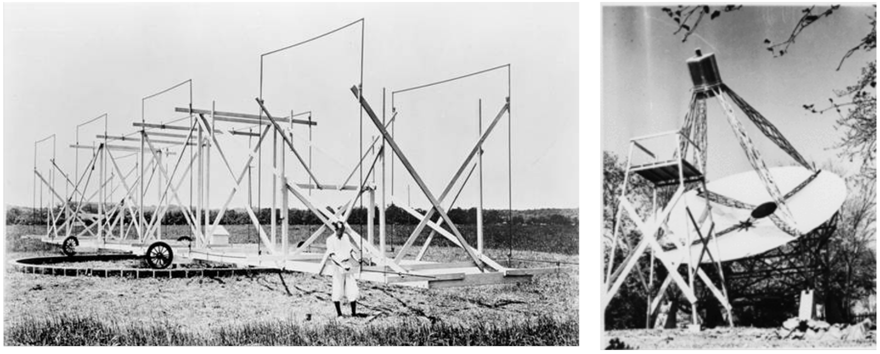

Figure 16: L: Jansky with his radio telescope used to discover radio emission from our Galaxy. R: Grote Reber's homemade 10m radio telescope.

astronomers were not interested in radio frequency observations and radio engineers were not interested in astronomy. Working in his spare time, Reber built a 10 m diameter radio dish and from 1938 to 1940 mapped the radio emissions of the Milky Way.

Radio astronomy received a boost in research interest following World War II due to the massive improvements in radio technology as a result of investment in radar and radio communications.

10.1 Single-dish telescopes

Dish antennas are similar to optical reflecting telescopes in that they use a parabolic (and in some cases, hyperbolic) reflector to focus electromagnetic radiation into a detector. As with optical telescopes, the larger the diameter of the dish, the greater the sensitivity and angular resolution of the telescope.

Radio telescopes are much larger than optical telescopes for two main reasons. Radio waves carry much less energy than optical wavelengths so a much larger collecting area is needed to make a sensitive telescope. Another reason is due to angular resolution. For example, a radio telescope observing radiation with a wavelength of 21 cm (an important emission in radio astronomy) would need to be approximately 800 m in diameter to achieve the same angular resolution as that of the human eye at optical frequencies.

Radio telescopes this large would be extremely expensive and difficult to build and to steer. Currently, the largest single dish telescope in the world is China’s 500 m diameter FAST Telescope. The dish is dug into a crater on top of a mountain and is “steered” by moving the receiver around above the stationary dish.

10.2 Interferometers — aperture synthesis

So how can we increase the sensitivity and resolution of our radio telescopes without making them impractically large? The answer is a technique called aperture synthesis.

Aperture synthesis is a technique in which the signals from two or more antennas are mixed in device called a correlator to produce a single output signal (also known as interferometry). The sensitivity of the combined system is improved since the total collecting area is the sum of the collecting areas of all of the antennas in the network.

The image produced from this technique will have an angular resolution equivalent to that of a single radio dish with a diameter equal to the separation between the furthest antennas. This means that signals from antennas sited thousands of kilometres apart can be combined into one image with incredible angular resolution.

This technique is also used in modern optical telescopes, though with much greater difficulty and with a much smaller number of receivers (at the time of writing, the record is 6).

11 Future telescopes

Bigger and more powerful telescopes allow us to study the Universe in ever greater detail and to unlock its secrets. Astronomers will continue to work to build more powerful telescopes for the foreseeable future. Within the next decade we have the James Webb Space Telescope (JWST, the successor to the HST. Hopefully JWST will be launched soon as it has been delayed numerous times) and the 39.3 m, imaginatively-named European Extremely Large Telescope (E-ELT) to advance optical astronomy. Sadly plans for a 100 m ‘Overwhelmingly Large Telescope’ (yes, really, this was a thing 10 years ago) were canned as the project was considered impractical.

Radio astronomers are looking forward to the completion of the SKA, as well as the Five hundred meter Aperture Spherical Telescope (FAST) in China, which will be the largest and most sensitive single-dish radio telescope. FAST is similar in design to the Arecibo telescope.

Interesting concepts for new types of telescopes in the more distant future include the Aragoscope, a space telescope which could use a huge (hundreds of metres or even tens of kilometres diameter), light-weight disk to focus light through the process of Fresnel diffraction. Another concept under investigation is the construction of space telescopes composed of smart dust, reflective particles shepherded by lasers into gigantic mirrors. Telescopes such as these could, theoretically, directly observe plasma exchanges between stars and the event-horizons of black holes.

A note on this font

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