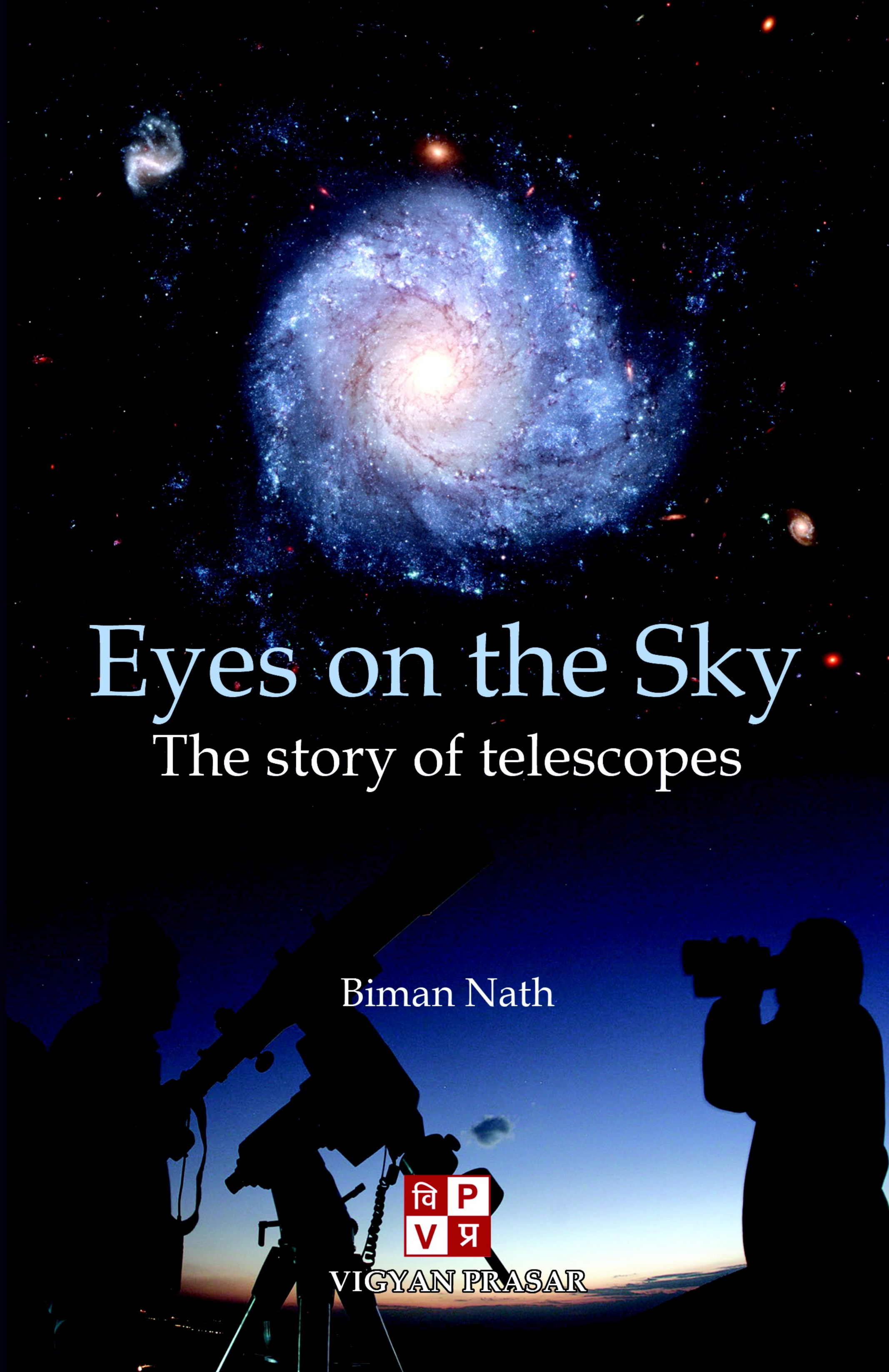

Eyes on the Sky

The story of telescopes

Biman Nath

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VIGYAN PRASAR

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Foreword

Of late, Vigyan Prasar has emerged as an important resource-cum-facility centre in the field of science communication. In addition to its regular programmes, Vigyan Prasar has undertaken special programmes and national campaigns built around celestial events like Total Solar Eclipse (1995, 1999) and Venus Transit (2004). Software developed on such occasions is extensively utilised by agencies involved in science communication across the country.

The year 2009 has been declared as the International Year of Astronomy (IYA-2009) coinciding with the 400th anniversary of the first astronomical observations with a telescope by Galileo Galilei and the publication of Johannes Kepler's *Astronomia nova* (*New Astronomy*). The central theme of the IYA-2009 is "The Universe Yours to Discover." It is important that all human beings realize the impact of astronomy and basic sciences on our daily lives, and understand how scientific knowledge can contribute to a more equitable and peaceful society.

The IYA-2009 aims to help people realize how astronomy has enriched almost every human culture and rediscover their place in the Universe through the day and night time sky, and thereby engage a personal sense of wonder and discovery. This will also serve as platform for making the general public aware about the recent astronomical discoveries and stimulate interest in astronomy. Throughout the year, activities would take place in each participating country at different levels.

Based on its past experience, Vigyan Prasar has initiated programmes with activities built around IYA-2009. The activities include production of a 52-episode radio serial in 19 Indian languages including English to be broadcast from 117 stations of All India Radio, a 26-episode television serial on astronomy, development of a variety of software including books, interactive CD-ROMs, and power-point presentations to be used as resource material during training programmes at different levels. An important part of the campaign would be the activities built around the total solar eclipse of 22 July 2009, which would be visible from some parts of India.

It is hoped the present series of publications brought out during IYA-2009 would be welcomed by science communicators, science clubs, resource persons, and individuals; and inspire them to discover the universe and realize their position in it.

Vinay B Kamble
Director
Vigyan Prasar

For my parents,
who gave me my first telescope
and changed my world forever.

1

Astronomy before telescopes

It is not often that one finds sharp transitions in history. Historical changes are slow and occur over a period of time, and the history of ideas in human thought is no exception. But one particular event stands out above all in the history of science.

In July 1609, Galileo Galilei used an instrument to look at stars, and the discoveries he reported changed not only the face of astronomy, but also that of science. His findings forever changed the way humans thought about the world around them. 1609 was indeed a watershed year in the history of human thought. Eight months after he first looked through his device, Galileo published a pamphlet, *"The Starry Messenger"*, in which he proved the ancient philosophers wrong. Such was the power of a single instrument that brought near the farthest corner of the universe. The seeds of modern science lay in that simple contraption called a telescope.

Telescopes have continued to usher new thoughts and ideas since that remarkable year. Scientists have built bigger and better telescopes in the centuries after Galileo, and the visions through every new telescope have changed our ideas about the universe. In the last century, scientists have even put telescopes in space to be able to observe the universe undeterred by the blanket of our atmosphere on Earth. They have also constructed telescopes to view the universe as it was never seen before, in wavelengths other than the visible, in radio, infrared, x-ray and gamma rays, and now they are building telescopes to detect waves in the geometry of space itself.

All this started from a simple set of observations Galileo did in 1609, holding his simple telescope. What did he see through his telescope? And how did they change our idea of the world around us? To understand the change brought about by the first telescope, we must look back at what people knew before its era.

Ancient astronomy

People from antiquity have looked up at stars for the simple reason of making a good calendar. Men needed to know when to sow seedlings and when to expect rains, and the movement of stars was the best way to keep track of the passage of time. Early Sumerians and Babylonians noticed that a few objects in the sky moved differently from the rest of the stars. They called them 'planets', which meant 'wanderers' in the sky. The five planets known to them were Mercury, Venus, Mars, Jupiter and Saturn, which along with the other two important celestial objects— the Sun and the Moon— shaped the early system of calendars.

The idea of five planets along with the Sun and the Moon gave birth to the seven day week. The first measures of a month were pegged to the waxing and waning of the moon[1], which takes approximately 29 days. Twelve lunar months added up to 354 days. But a year— the time taken by the Sun to return to its initial position in the sky— was longer than that. So discrepancies arose, and ancient people learned to correct their calendars by adding an extra month whenever they felt it was needed to do so. At the same time,

[1] The words 'month' and 'moon' were derived from the same root.

they continued their observations of stars so that they could come up with a calendar that would correct itself.

Gradually, the ancient scholars began to construct a 'model' of the universe in order to understand it better and to predict astronomical events more accurately. Eudoxus of Cnidus, a student of Plato, came up with a model, which was further revised by Aristotle in the 4th century BC. In the Greek model of the universe, the Earth was at the centre, and the Sun, the Moon, the planets and the stars revolved around it in fixed, circular orbits at different distances from the Earth (Figure 1).

This model of the universe might look absurdly naive to us now, but we must appreciate that one must begin with a simple model when faced with a complex phenomenon. One can improve upon the model and add more complicated

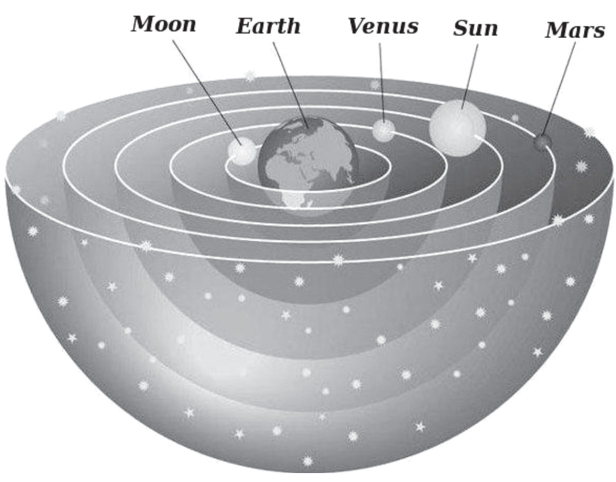


Figure 1: In the geocentric model of the solar system, a set of spheres were imagined to hold the Sun, the planets and the stars. These spheres revolved at different speeds around the Earth to account for the rising and setting of celestial objects every day.

features after further tests and observations, which may or may not tally with the predictions of the first model. A circle was the simplest conceivable path for an orbit, so the Greeks chose to think of circular orbits. Also, at first sight the Earth appears to be fixed, and so one tended to think in terms of a fixed Earth and everything going around it.

Added to this *geometric* model, Aristotle introduced a *physical* model of the universe, to explain 'why' things moved the way they did. The Aristotelian universe was thought to be made up of five basic elements: earth, fire, air and water for terrestrial objects, and a pure, 'fifth essence' (quintessence) for celestial objects. All these elements had their 'natural' places of rest, and things moved to seek their natural places. So, objects fell on the Earth because that was their natural place to be, and hot air moved up because it was the mixture of air and fire, whose natural place was high above the Earth.

Not everyone subscribed to these ideas though. There was Aristarchus of Samos who in the 3rd century BC found a brilliant method for estimating the distance of Sun and Moon from the Earth, and determining their sizes compared to Earth. (The circumference of the Earth had already been estimated by Eratosthenes in the 3rd century BC.) He showed that the Sun was much bigger than the Earth, and thought it absurd that a giant Sun should go around a tiny Earth. His ideas found resonance later in the thoughts of the Indian scholar Aryabhata, who reiterated the idea of a moving earth in the 5th century AD.

But the majority of ancient astronomers continued to think in terms of a fixed Earth at the centre of the universe. The reason was that a lot of importance was given to pure thought over testing the results with active experimentation and observations. It was not that people in the antiquity did not do accurate observations. On the contrary, the discovery of the precession of the axis of the Earth by Hipparchus in the 2nd century BC was the result of painstaking and careful observations. He had discovered that the direction of the axis of the Earth did not remain fixed in the sky, but rotated like a top with a period of approximately 26,000 years. This resulted in making the apparent positions of stars shift by an arc minute (one sixtieth part of a degree) a year[2].

Careful observations of some planets did come up with a problem for the simple Aristotelian model of planets revolving around the Earth in circles. Some planets like Mars

Figure 2: The retrograde motion of Mars is shown in this picture using photographs taken over a few months in 2005.

appeared to abruptly change their direction of motion in the sky and then revert back to the original direction after making a loop (Figure 2). This is known as the 'retrograde' motion of planets.

2 Hipparchus actually discovered that the equinoxes and solstices shifted, but the interpretation of this being due to the rotation of Earth's axis came much later. Also, there was confusion about whether the shift was cyclic or oscillatory, or some other nature.

The Greeks tried to explain this peculiar apparent motion by adding a feature in their geocentric model. They argued that perhaps the orbit of a planet was not a simple circle, but had a smaller circle added to it. They called the big circle 'deferent', and the smaller circle 'epicycle'. The centre of the epicycle revolved with a uniform circular motion, along the deferent, but the planet, in its motion on the epicycle, would go 'backward' for a while, which would explain the retrograde motion. But the predictions never quite matched the observations, so the Greeks kept on adding such 'epicycles' to help close the gap (Figure 3). At no point though did the Greeks question their hypothesis of putting the Earth at the centre, or the idea of circular orbits.

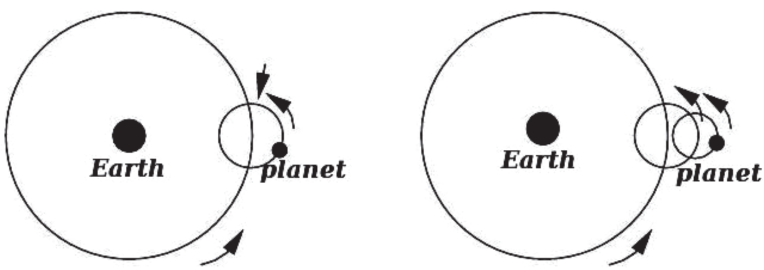


Figure 3: The orbit of a planet with an epicycle (left), and with an epicycle on epicycle (right).

When the centre of scholarly research in Greece moved to Alexandria, Ptolemy wrote a book, *The Great Treatise*, in 2nd century AD, in which he compiled what was known in astronomy until then. In the final model of Ptolemy, there was another complicated feature in addition to the epicycles. The Earth was shifted a bit from the centre of the deferents (the big circles on which the epicycles moved).

There was one aspect of Ptolemy's work that was symptomatic of scientific research in ancient times, and which is in stark contrast to the foundations of modern science. Ptolemy often did not care to compare the predictions of his models with actual observations, and either cited old observations (usually by Hipparchus) or simply stated the results of his calculations as if they were measured data. Since the theory and observations were presented in a manner that they were a perfect match, Ptolemy's book acquired an aura of authority and it remained a standard text for several centuries after astronomical research in Greece came to an end with the burning of the famous library in Alexandria in 7th century AD.

Medieval astronomy

The centre of research in astronomy by then had moved eastward, to India and then to the Arabic countries. The Greek ideas were reviewed in India (for example, in Varahamihira's *Paulisa-siddhanta,* circa 6th century AD). In 9th century AD, during the reign of Harun-al-Rashid in Baghdad, Ptolemy's book was translated into Arabic as *Al-kitabu-l-mijisti*, which meant 'The Great Book'. Chinese and Korean astronomers also kept regular records of astronomical observations from antiquity.

Figure 4: An astrolabe made by Arabic astronomers.

Arabic astronomers improved upon many Greek instruments. The Greeks had made instruments to determine the days of the year when the day and nights were equally long. They also invented a wonderful instrument called *astrolabe* with which one could determine angles between the stars and also perform calculations involving spherical astronomy (Figure 4). This instrument was later improved upon by Arabic astronomers, and became an essential tool for navigators[3].

Arabic scholars built on the advances made by Indian mathematicians and incorporated them into their study of astronomy. Ptolemy's book was primitive in its use of mathematics, with no decimal notation in it, for example, and was difficult to use. In their attempts, Arabic astronomers improved upon the mathematical calculations for the Ptolemaic models, and even made alternative suggestions to Ptolemaic models, notably by Ibn al-Shatir of Damascus in the 14th century AD.

The improvements made by the Arabic astronomers came into the hands of Europeans after the Crusades. Ptolemy's book was translated into Latin, which is now known as *The Almagest* (derived from the Arabic *Almajasti*[4]). The fervour of the Crusades was at its peak then, and the old ideas were incorporated into Christian theology by Thomas Aquinas in the 13th century AD. It then became impossible to question the Aristotelian ideas, as it became equivalent to doubting the authority of the church.

3 It was easy to determine one's latitude if one knew the position of stars in the sky. One could also estimate the longitude if one had some idea of the time.

4 As a matter of fact, this process of translation introduced many words into astronomy which are nothing but mangled Arabic words, like the name of the stars Algol or Aldebaran.

Astronomy in Europe

Figure 5: Russian stamp commemorating Ulugh Beg, with a picture of his Samarkand observatory.

One of the first independent European endeavours in astronomy in the medieval era was the making of a calendar at the behest of the Spanish king Alfonso X in 1252, which was carried out according to the rules of Arabic astronomers. It was only after a few centuries that European astronomers became proficient enough to make observations that could rival old data. In the middle of 15th century AD, astronomers like Regiomontanus of Germany and Georg Purbach of Vienna began to make and use precise instruments. Around the same time, Ulugh Beg build a big observatory in Samarkand (Figure 5).

Then in 1543, Nicolas Copernicus from Poland wrote a book challenging the ancient ideas about the solar system. In the Copernican system, the Earth rotated around its axis once a day and it revolved around the Sun once a year. This model explained the retrograde motion in an elegant manner, without using any epicycles. According to the Copernican system, the Earth overtook an outer planet like Mars from time to time, and from the point of view of a terrestrial observer, Mars would appear to move *backward* for a period of time against the backdrop of fixed stars (see Figure 6). One did not need the complicated system of epicycles; just putting the Sun at the centre was enough to explain it.

It was heretical in those times to think of the universe in such a manner. But within a few decades, another astronomer dealt a second blow to the ancient ideas. This time the concept of circular orbits was at stake.

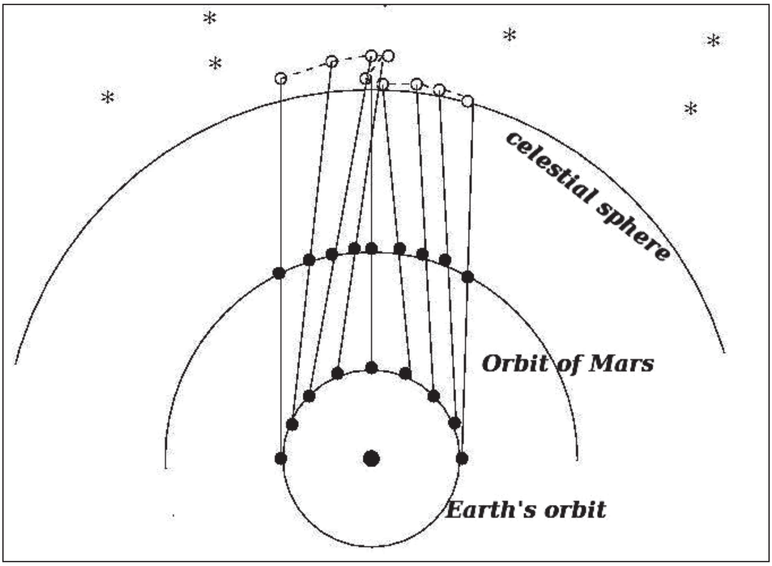


Figure 6: The retrograde motion of planets was explained in a simple manner in the Copernican model of the solar system. The Earth overtook an outer planet like Mars from time to time, on their orbits around the Sun. During the time of overtaking, Mars would appear to move 'backwards' as seen from the Earth.

Following the development of precision instruments, Tycho Brahe built a great observatory in Denmark in 1576. Tycho was a systematic and rigorous observer, and carried out observations which were accurate to approximately an arc minute (1/60th of a degree). He had already created a furore in Europe by his observation of what he called a Nova, or a 'new star'. Tycho observed this bright object that appeared almost out of nowhere in the constellation of Cassiopeia in 1572. He described it in a book '*Stella Nova*', and proved that it did not have anything to do with the atmosphere on Earth, but was a distant, celestial object. In the Aristotelian universe, celestial objects were made of pure quintessence, which did not change or decay. The sudden occurrence of a luminous object in the sky contradicted the ideas of the Aristotelian universe.

But Tycho's detailed observations were soon going to prove even more disastrous for the ancient ideas. Johannes Kepler was Tycho's assistant; he used Tycho's data after his death, and tried to find a suitable model for the solar system based on the data. By the end of 1605 AD, Kepler found that he could better fit the data for Mars if he used an elliptical orbit, and not circular. An ellipse is a curve, the sum of whose distance from a set of two points (called the foci) is a constant (Figure 7).

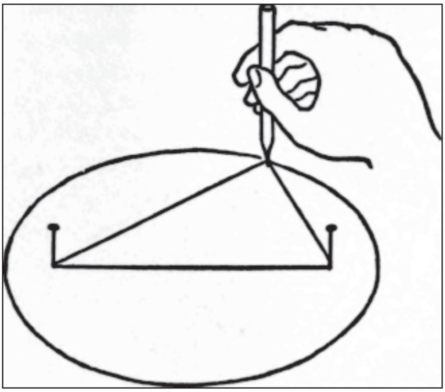


Figure 7: The sum of distances of the points on an ellipse to the two foci is a constant. One way to draw an ellipse is to tie a thread around two fixed foci and draw a curve with a pencil, keeping the thread taut at all times.

Kepler put the Sun at one of the foci of the orbit of Mars and other planets. Then he found two extraordinary relations for the orbits. One was that the planets moved the slowest when they were farthest from the Sun; in fact a straight line joining the Sun and the planets would sweep equal areas in equal intervals of time. Another was that the square of the period of revolution of a planet were proportional to the cube of its average distance from the Sun (which he discovered in 1618).

Kepler published the first two laws in a book *Astronomia Nova* (New Astronomy) in 1609. This was a powerful argument against the ancient ideas, but it was still something that came from the *interpretation* of data. People needed something more direct, more visually mind-blowing to be able to discard the age-old ideas.

The same year Galileo Galilei in Italy built a telescope that did precisely that, and changed modern science forever.

2

The invention of telescope

The earliest description of lenses and spectacles dates from 14th century AD. Manufacturing of glass had become relatively cheap by then, and Florence and Venice, in particular, had become centres of polishing and grinding glasses. Craftsmen had begun to make disks of glasses which were convex on both sides, put them on metal frames and sold them to old people who had difficulty reading because they could not focus on nearby objects. They called these disks '*lentils of glass*', because of their shape, or (from the Latin of lentils) '*lenses*'. As a matter of fact, wearing spectacles became a symbol of learning as scholars used them extensively.

A lens can be imagined to be made of several prisms of different shapes, which refract light falling on them at different angles. A convex, or converging, lens is such that parallel rays of light are refracted into coming *together* at a

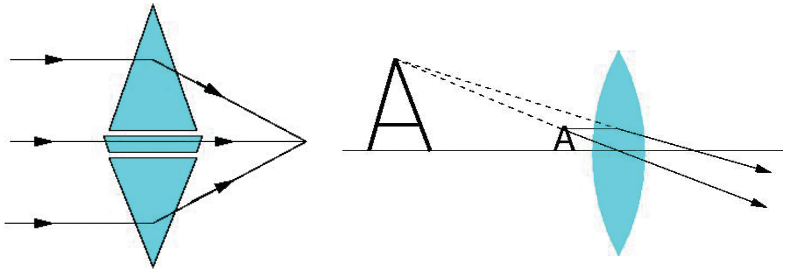


Figure 8: A convex lens can be thought of a combination of prisms of different widths so that light rays converge after passing through it (left). An object kept close to a convex lens and viewed through it appears bigger (right).

spot. Conversely, an emerging set of rays from an object held close to the lens are refracted in such a manner that the rays are bunched together, so that the object appears to be *bigger* to the viewer. This is how a convex lens acts as a magnifying glass (Figure 8).

A couple of centuries later, Italian lens makers perfected the making of concave lenses which do the opposite: they cause a set of incoming parallel rays of light

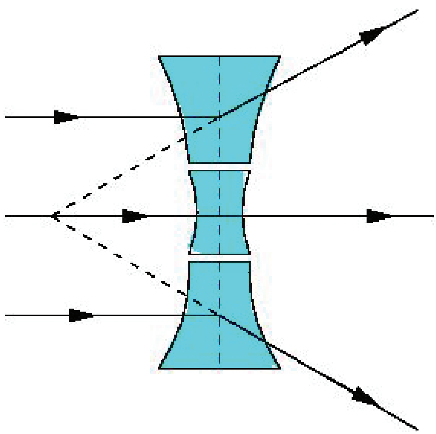


Figure 9: A concave lens makes light rays passing through it diverge. Its properties can be understood by imagining it as a stack of prisms, in an order opposite to that of a convex lens.

to *diverge.* A concave lens can also be thought of as a stack of prism of different widths, but in an order opposite to that of a convex lens. A set of parallel, or near parallel rays are made to diverge when they pass through a concave lens (Figure 9). Lens makers began to make spectacles of concave lenses for myopic people, who were short-sighted and needed help in seeing distant objects clearly.

Spy-glass

It so happened that the least used lenses in the collection of a lens maker were a weak magnifying glass (which made rays converge slightly) and a strong concave lens, because long sighted and short sighted people needed either a strong convex lens or a weak concave lens. It is therefore not surprising that, in the course of working with lenses, or toying with them at their leisure time, lens makers would notice a curious phenomenon. When they held their least used lenses (a weak convex and a strong

Figure 10: Spectacle vendors in an engraving by Johannes Collaert, 1582.

concave lens) together in a line, with the concave lens near the eye, then a distant object appeared bigger than normal (Figure 11). The fact that a distant object looked big had tremendous implications.

A Dutch lens maker named Hans Lippershey is credited to have made this discovery. He filed a patent application for a device for '*seeing faraway things as though nearby*' in October 1608. His device magnified distant object three or four times, and consisted of a convex and concave lens inside a 50-cm long tube of diameter 3-4 centimetre. At the same time, two other lens makers named Jacob Metius and Zacharias Janssen also claimed to have made similar devices although they did not apply for patents. The General Estates of The Hague did not award any patent to Lippershey after hearing the claims from others, but they did commission Lippershey to make several versions of his 'device'.

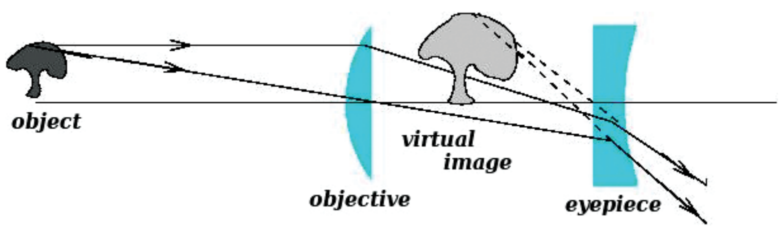


Figure 11: The spy-glass of Lippershey used a convex and a concave lens to make distant object look bigger. The rays emerging from the concave lens kept near the eye (called the eye-piece) made the rays diverge, so that the viewer appears to see an image (a virtual image). The angle subtended by the image at the eye is much bigger than that by the original subject at a distance.

The news of this discovery spread quickly through Europe. Janssen had sold some of his devices at the Frankfurt fair. Shops in France and Italy began to sell these 'spy-glasses' by 1609 (it was not called 'telescope' until 1612 [1]).

Galileo made his own telescope in June 1609, and within a few months, constructed a better telescope with an eight-

[1] Ioannes Dimisiani, a Greek mathematician, suggested the name, which means 'far-looker' in Greek.

fold magnification power. By October, he had mastered the art of making even better telescopes, and built one with a magnification power of twenty. He was now ready to try looking not just at distant objects on Earth, but up at the sky.

And what he saw revolutionised astronomy.

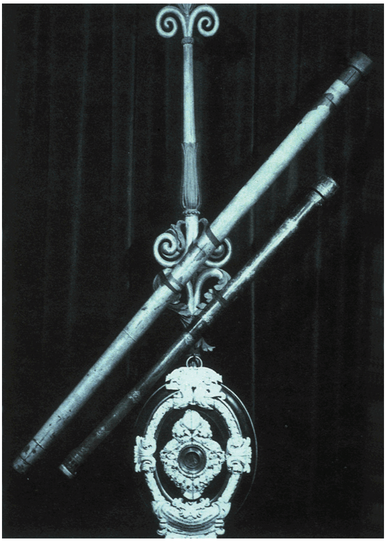


Figure 12: Galileo's telescope.

Galileo's observations

Galileo mentioned in *The Starry Messenger* (1610) a set of four observations with his telescope. First, he claimed that the Milky Way was not a fuzzy band of light across the sky, but a collection of myriad stars. Second, he could see stars, not just a few but many, in *any* direction of the sky in which he pointed his telescope. Already there were seeds of a revolution here: that the universe was not as it *seemed* to the naked eye. All previous notions of the universe were based on how it *appeared* to the unaided eye, and that was set to change now.

Galileo's third observation concerned the Moon. He was surprised to find that it was far from being a perfect sphere, and was rough and mountainous. This was yet another blow to the ancient ideas, that a sphere was the most perfect form and so all celestial bodies ought to be spherical. Galileo's last observation in 1609 was of the planet Jupiter. He noticed four specks of light going around it from his observations carried over days and weeks. This was a fatal news for the

Aristotelian world in which *everything* was required to go around the Earth. Here was an object in the sky with its own retinue, so why could not the Sun, as Copernicus had argued half a century before Galileo, be at the centre of the solar system?

Galileo found a definite proof for the Copernican system during the autumn of 1610 when he turned his telescope towards Venus. He discovered that Venus had phases just like that of the Moon, and he could explain it simply with the Copernican model. In the ancient system, Venus moved on an epicycle whose centre was always between the Sun and the Earth, and so Venus would always appear as an illuminated crescent, never the phase of being almost fully illuminated, which was what Galileo saw, and which the Copernican system could easily explain (Figure 13).

Then came Galileo's observations of sunspots. By this time others had got hold of telescopes and observed the Sun.

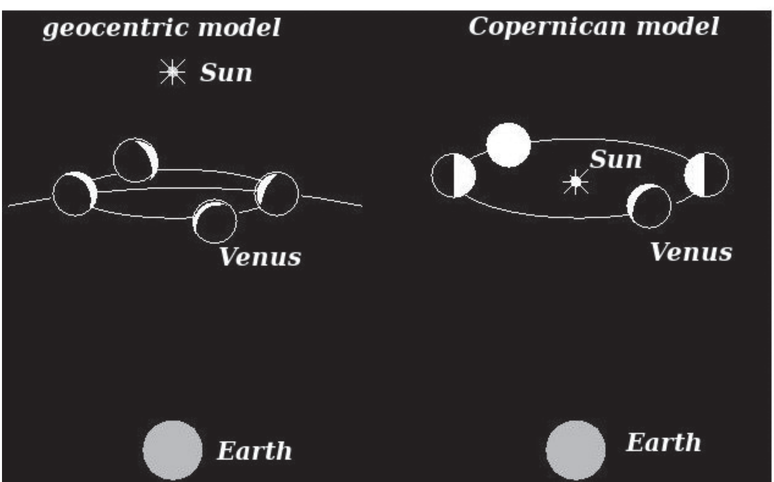


Figure 13: Galileo's observation of phases of Venus could be explained by the Copernican model and not by geocentric model of the Greeks.

A Jesuit named Christoph Scheiner projected the image of the Sun onto a white screen, while Thomas Harriot in England risked his eyesight to look direct at the Sun through his telescope. A Dutchman named Johann Fabricius and Galileo both noted that there were spots on the Sun (which was contradictory to the Aristotelian view that celestial objects were pure and unblemished), and that the spots changed their positions from day to day. This implied that the Sun rotated on its axis. If the Sun could rotate, then why could not the Earth? And if the Earth rotated around its own axis, then one did not need the Sun to revolve around it to explain the cycle of day and night[2].

The flurry of these discoveries dealt such a blow to the existing ideas that in the year 1616 the Church put the old book by Copernicus in their list of forbidden books. Galileo was warned not to meddle with existing ideas of the universe that were part of the doctrine of the Church. But Galileo's observations, together with the earlier works of Copernicus and Kepler, had ushered in a new era whose march could not be stopped by any force in the world now. In four years' time, Francis Bacon would write his *Novum Organum*, which was a manifesto of the philosophy of modern science: that the test of truth should be experiment and observation and nothing else.

2 Galileo also discovered that Saturn appeared to have two moons but they did not move. He was puzzled when after a few years he did not find them, and he wrote in his note book: has Saturn devoured his children?

3

Early telescopes (17th century)

The Galilean telescope had a small problem. Galileo had designed it in order to get a large magnification power, but it reduced the 'field of view'— the portion of the sky he could see at once through his telescope. The design was such that the light from objects slightly off the telescope axis emerged from the (concave) eyepiece at such a steep angle that it missed the pupil of the observer's eye, and those objects could not be observed. When Kepler came to know of the recent invention, within a couple of years he devised a better combination of lenses that increased the field of view. Instead of a concave lens as the eyepiece, he used a convex lens. So he had two convex lenses at the two ends of a tube (Figure 14). In a sense, it produced an image of a star through the first lens, and this image was examined by another magnifying lens.

Early innovations

Then two additional convex lenses were added to make the image the right way up, to make telescopes for terrestrial use. It was not much use for astronomy because the

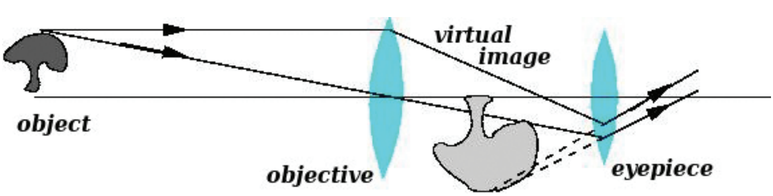


Figure 14: Kepler used a convex lens as the eyepiece and increased the field-of-view of telescopes.

additional lenses decreased the brightness of the image (since glass absorbed a fraction of the light). These developments led to a spurt in experimentation with lenses, and Snell's law of refraction was discovered, for example.

Johannes Havelius of Danzig showed that lenses with strongly curved surfaces produced bad images, and it was better to have a weak, slightly curved objective lens (the one through which distant light rays first enter the telescope). But a weak objective brought light to focus at a large distance, and so one needed a long tube. Havelius built a telescope that was about 3 metres long, with which he made the first map of the Moon (published in his *Selenographia* in 1647). His attempts at making even longer telescopes were not so successful though; they became rather unwieldy (Figure 15).

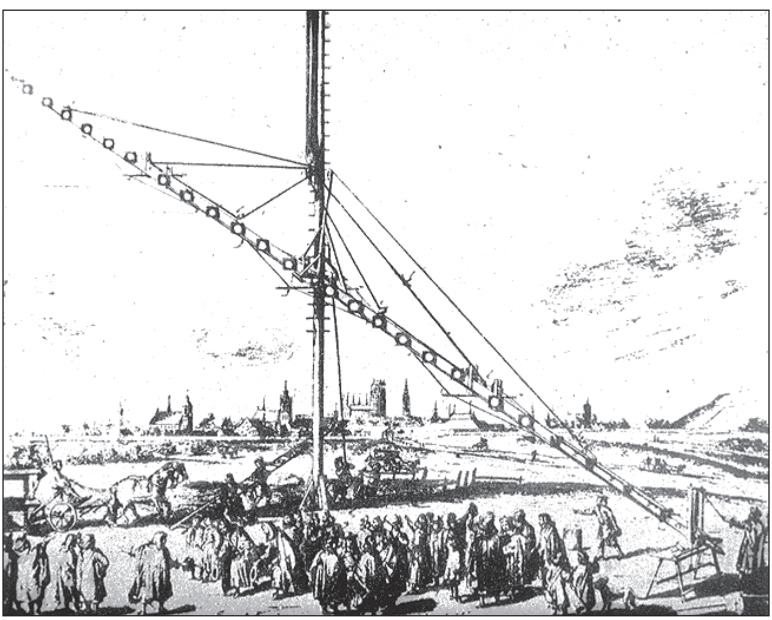


Figure 15: A 140-feet long telescope at Danzig built by Havelius.

Christian Huygens in Holland experimented with better methods of grinding and polishing with gears, and made good quality lenses of long focal lengths. In 1655, he discovered Titan, the largest moon of Saturn. After a few years, he explained the puzzling observations made by Galileo, claiming that Saturn had 'a ring, thin, plane, nowhere attached'. Soon Giovanni Cassini observed a large gap in the ring around Saturn in 1675, which is now called 'Cassini's division', as well as features on other planets like Mars and Venus. He found that all planets rotated around their axes.

Huygens also invented the pendulum clock, which together with the telescope became the essential tools of astronomers (because they needed an accurate clock to keep track of the position of stars as the Earth moved). Huygens also discovered a problem that would bedevil the astronomers ever since the first telescope was made. He found that the quality of image was affected by air currents in the atmosphere. This problem, called 'seeing', is the reason why modern astronomers build their telescopes on mountains or oceanic islands of Hawaii or the Canaries, above most of the atmospheric turbulence.

Reflecting telescope

Interestingly, the biggest advancement in telescope design came from the greatest theoretical scientist of that time. Isaac Newton found that there was a fundamental limit to the performance of a telescope that came from the property of glass used for the objective lens. A 10-metre telescope was better than a 5-metre one, but the increase in the length made worse the mechanical problems associated with it. Newton published his results in 1672, saying that 'the improvement of telescopes by refractions is desperate'.

He then proposed a solution using a concave *mirror*, rather than a lens, to collect and focus light. A concave mirror gathers light into a focus by reflection, just as a convex lens gathered them into focus by refraction. The process of reflection made the light rays traverse the length of the tube again, in the *opposite* direction, and helped one avoid the problem of making the telescope too long, which is unavoidable in a refracting telescope. The only problem was that the observer would have to peer down the length of the telescope, thereby obstructing the light rays from stars. Newton had a brilliant solution in mind. He diverted the focussed rays from the tube by putting a small plane mirror (called secondary) in the tube to reflect it out of the tube (Figure 16).

He showed his first reflecting telescope in 1672, and it created quite a stir. His telescope was small, just about 30 centimetres long, but with a magnification power of 40: it was better than a metre long refracting telescope! The big telescopes made by Havelius and others suddenly looked

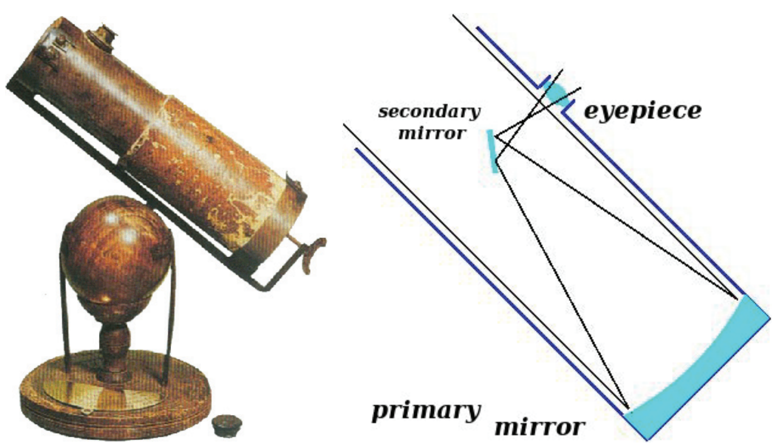


Figure 16: Newton's reflecting telescope.

like obsolete dinosaurs in comparison with the versatile reflecting telescope of Newton.

Newton's telescope also solved another problem faced by astronomers. A convex lens gathered rays of different colours at slightly different points. Considering a lens as a combination of prisms would readily convince one that this must happen. In other words, all colours were *not* brought to a single focus. As a result of this, the image seen through the eyepiece had a coloured haze around it. This problem is known as 'chromatic aberration', and it was usually solved by putting an extra lens alongside the convex lens (Figure 17). But there was no such problem in the case of reflection

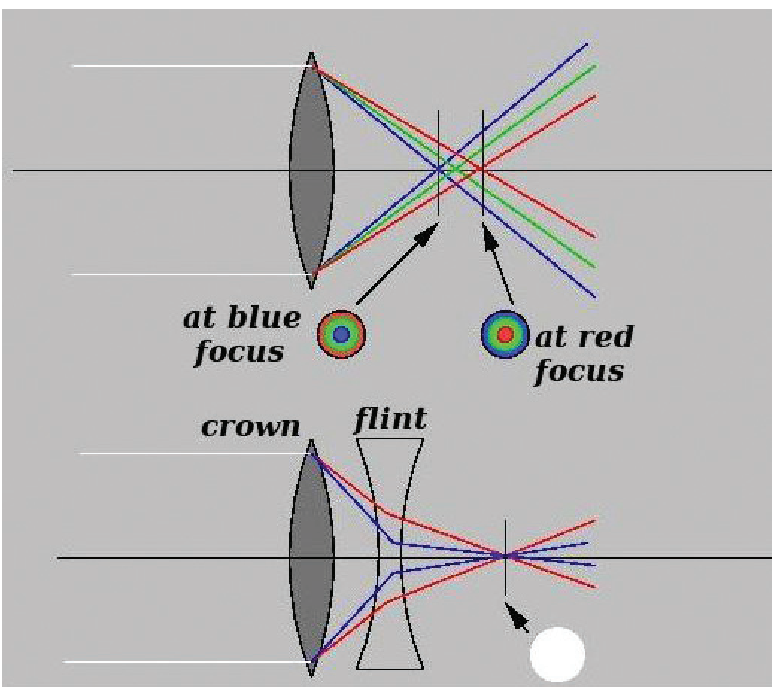


Figure 17: The problem of 'chromatic aberration', of the inability of lenses to focus rays of different colours at one place, is usually circumvented by using an extra lens.

from a mirror. So Newton's reflecting telescope brought different colours of light to a sharp point. The only problem was that the mirrors of 17th century were not good reflectors. Silvered glass was not discovered until about two centuries later. So Newton had to experiment with various metal alloys for his mirror.

After Newton's invention, there was a flurry of activity around the new reflecting telescope. James Gregory of Scotland came up with an alternative design in 1665 in which the secondary mirror was concave, and the primary was perforated at the centre to allow light to pass through it to an eyepiece. Soon in 1672, Laurent Cassegrain of France came up with another design using a convex secondary mirror, which helped make the telescope even more compact for the same power of magnification (Figure 18).

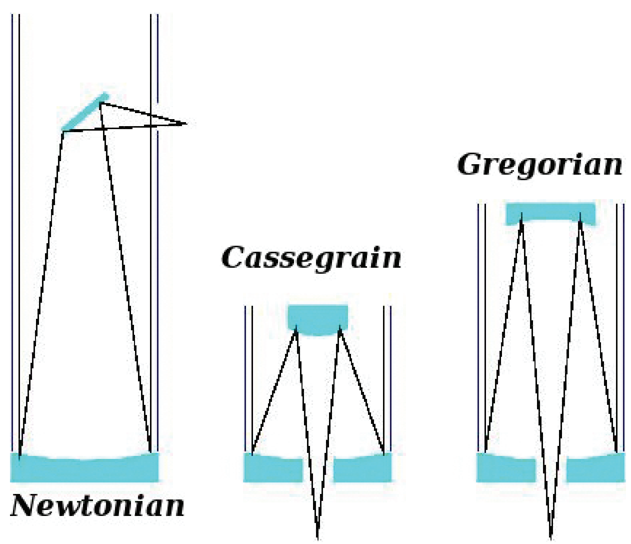


Figure 18: In a Cassegrain telescope, a convex mirror is used as a secondary, which magnifies the image formed by the primary mirror. The image is directed back through a hole in the primary to a convenient location behind, where eyepieces and other equipments can be placed. In the Gregorian design, the secondary is a concave mirror.

Measurement with telescopes

It was not enough though to build telescopes for better images if what was seen could not be *measured.* The hallmark of modern science— as previously shown by Tycho Brahe's careful observations and Kepler's deduction from them— was doing careful observations and recording the data. Without measurement, astronomical observations would have amounted to mere stamp collection, viewing one beautiful image of celestial objects after another. One needed to measure things to be able to test them against hypotheses and improve upon existing theories. But the earliest telescopes had low quality lenses and mirrors, and observers could not always trust the images they saw with their eyes.

The most accurate astronomical instrument available at the time of Galileo was the sextant. The development in technology needed to make better instruments was however hampered because of the Thirty Year War in Europe (1618-1648). Scientists in England and France fared relatively better at this time. One of the first steps in making accurate measuring instruments came from the work of Pierre Vernier in France, who developed a graduated scale of angles that could be read accurately. Vernier used an extra short scale marked in slightly different intervals from a main scale, and when mounted on an astronomical instrument, it made it possible to read an angle to an accuracy of an arc minute (1/60th of a degree) when the main scale was marked at the interval of only half a degree. Jean Baptiste Morin of Paris was the first person to put the Vernier scale on a telescope.

In England, William Gascoigne made an interesting chance discovery in 1639. A spider had accidentally spun its web within his (Keplerian) telescope exactly at the common focus of the two lenses. So it was magnified by the eyepiece exactly the same way as the image of a star. Then he realised that if he put at this place in the telescope a thin 'cross-hair'— two thin wires perpendicular to one another and graduated into fine scale— then he would be able to make measurements *in* the image. Since the cross-hair and the image were at the *same* position, the eye did not have to focus alternately on distant star and the cross-hair, which was the case for instruments before the telescope era. Also, the same magnification for the image and the cross-hair implied that one could measure very small angles than what one could do with naked eye. Gascoigne also added a candle to the telescope to illuminate the cross-hair, and developed the first eye-piece micrometer. With these additions he was able to make definitive observations on the apparent decrease and increase in the size of planets as they came near and went away from Earth.

At this point of time, the need for an accurate method of determining the longitude for navigating ships gave spurt to efforts in astronomical observations and in making better instruments. People had realised by this time that technological spin-offs from scientific experimentation were useful. Scientists made better microscopes, thermometers, barometers, and sponsorship became gradually available to carry out better and more accurate experiments.

The problem of determining longitude was of prime importance. It was easy to determine one's latitude from observing stars, but longitude was a different story. One needed to keep track of the time difference between two places to determine the difference in longitude between them. For a navigator, it was extremely difficult to determine at the time of his observations at sea, what time it was at the port he had left many months earlier. For example, if the navigator found out somehow that when it was 6 am at Greenwich, it was exactly noon at the position of his ship (say, judging from the position of the Sun being at the maximum altitude), then he could say he was a quarter of the globe away from Greenwich, or 90 degrees east or west of Greenwich. (He would have to decide between the Pacific and the Indian Ocean though!) But no accurate clock was available for a 17th century sailor. Huygen's pendulum clock did not help much on a rolling ship. Some suggested the use of celestial objects, like the Moon. Sieur de St Pierre of London suggested that if he had the data of the Moon's position against the stars, he would be able to derive the longitude.

Then King Charles II ordered the Royal Society to supply him the data in 1674, and appointed John Flamsteed for this purpose. Flamsteed was unimpressed by the idea, and proved that using just the Moon's position— as recorded by Havelius at that time— one would incorrectly predict longitudes and make mistakes of the order of 500 kilometres or more. What one needed was to have a better catalogue of stars, more accurate than that of Tycho Brahe, and one would need a better observatory for that. Flamsteed, who was then made the Royal astronomer, argued for an observatory at Greenwich, which was built in 1676, but he had a hard time convincing the King to pay for good and accurate instruments to be put in it.

At around the same time, a Danish astronomer named Ole Römer made some significant advancement at the Paris observatory. He built a transit telescope, with which one could observe stars or planets as they crossed the north-south line in the sky (the meridian). Then he made an equatorially mounted telescope, which was so mounted that one axis pointed at the north celestial pole (towards the North Star). The effect of rotation of the Earth was compensated by rotating the telescope around the polar axis, and it made it easy to observe (Figure 19).

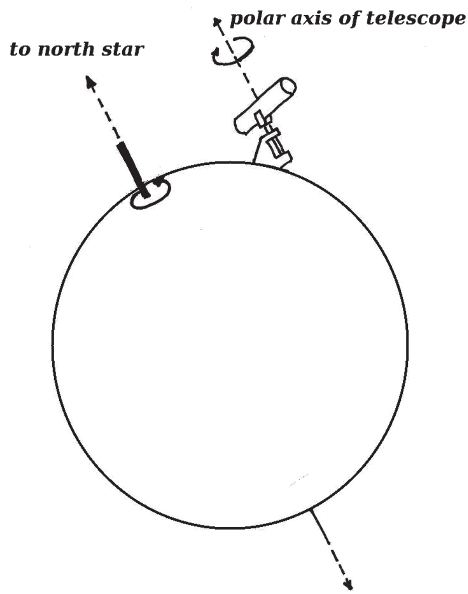


Figure 19: The equatorial mounted telescope greatly eased observations. The axis of the telescope is made parallel to the Earth's axis, and it swings in the direction of celestial north-south and east-west, and therefore can be made to follow the stars as the earth rotates by turning only one axis. In the earlier, altitude-azimuth mount (called alt-azimuth mount), one had to turn the telescope around two different axes to be able to follow a star as the Earth rotated.

Another noteworthy development in astronomy, and science in general, was the publication of Newton's work on gravitation. Edmund Halley persuaded Newton to publish and paid for it. The *Principia Mathematica* ushered in another revolution in natural philosophy by positing the idea of universal gravitation, that the motion of the Moon around the Earth was governed by the same rule as that of an apple falling to the ground. Newton showed that Kepler's laws were a natural consequence of these laws of gravitation.

Then there was a naval disaster in 1707 that alarmed the patrons of marine trade. A British fleet was lost near Sicily, and it was attributed to the defects in the measurement of longitude at that time. Flamsteed was urged to quickly publish his catalogue of stellar position, to be used by sailors at sea, but he refused to hurry into publishing inaccurate data. His catalogue finally came out in 1725, six years after his death, containing the positions of 3,000 stars, but it failed to make any impact. One reason was that, as Halley showed in 1718 by comparing the observed positions of bright stars like Sirius with those from Hipparchus's time, the positions of some stars were not fixed, but they changed over centuries.

Earth does move

Some astronomers began to study these shifts in the positions of stars. There was an idea to use these shifts to find out the distances to stars. The idea began with Copernicus himself. The apparent position of a star was bound to change as the Earth moved in its orbit around the Sun (Figure 20). Copernicus had initially attempted to observe this shift, called parallax, but failed to see it.

Samuel Molyneux and James Bradley built an instrument with which they thought they could detect tiny shifts in the positions of stars. Stars overhead at a given place were best suited for this study. They invented the 'zenith sector' that pointed vertically upward, to observe stars directly overhead. It was free from mechanical distortion, which was a frequent problem in other telescopes due to flexure of heavy material used for the tube. The image produced by it suffered less distortions from atmospheric refraction, because the vertical line of sight was the shortest path through the atmosphere.

In 1725, Bradley and Molyneux found that the position of the star Gamma Draconis (the third brightest star in the

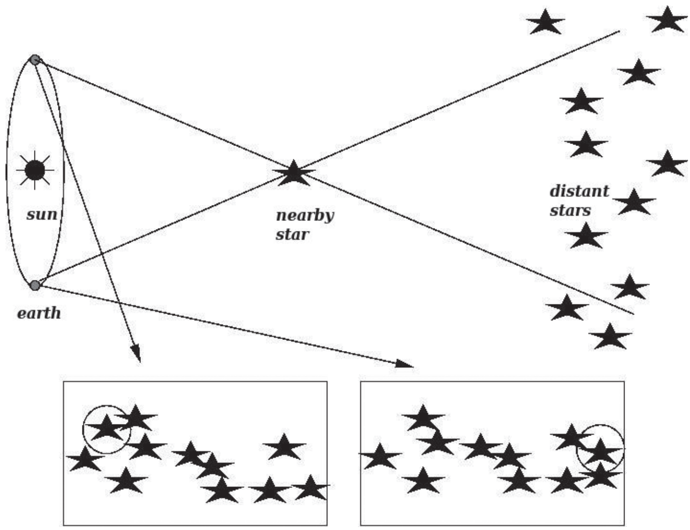


Figure 20: A star would appear to change its position in the background of distant stars from the point of view of observers on Earth, during the motion of the Earth in its orbit. The nearer the star to solar system, the larger would be the parallax or the apparent shift in its position. In the example shown above, a nearby star appears to 'shift' —as shown by the encircled star in the two views of the sky six months apart.

constellation Draco), which crossed the zenith above London, changed between December and March, and the difference was approximately twenty arc seconds (one arc second was 1/60th of an arc minute, and 1/3600th of a degree), but it was in a *different* direction than predicted by parallax.

As a matter of fact, Bradley and Molyneux had discovered what is now called aberration of light due to the *motion* of Earth in its orbit. Just as a person running through rain must bend his umbrella in the forward direction to keep himself dry, a vertical telescope also must lean at an angle to catch the light from a distant star, being hurried along by the motion of the Earth. This was the first, concrete proof that Earth did move around the Sun (Figure 21).

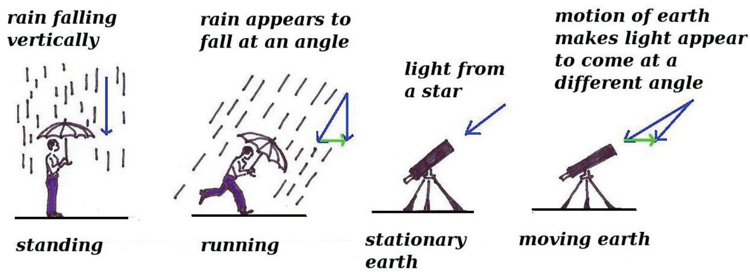


Figure 21: Bradley's observation of stellar aberration was the first concrete proof of the motion of the Earth. One can understand it with an analogy of running in rain. For a running person, rain falling vertically would appear to fall at an angle: his velocity (shown by a green arrow on top) changes the direction of falling rain (blue arrows), so that it appears to be slanted in his frame of reference. Similarly, the light from a star would appear to come at a different angle on a moving earth, than it would have on a stationary earth. The difference in the angle depends on the Earth's velocity.

Bradley's hope of measuring the distances of stars would have to wait for another century. He could console himself by estimating the *minimum* distance of the star Gamma Draconis though. He argued that the parallax must be less than one arc second, which implied that the star was at least (if not more) at an amazing distance of 30,000 billion kilometres, a vast distance indeed in the reckoning of eighteenth century scientists.

Suddenly, the universe had expanded, as it were, to engulf a vastness never known to mankind before. It was not enough to study the rotations of planets in the solar system. A whole universe of stars came within the reach of astronomers— and not just stars, but also distant galaxies. Soon after Galileo's initial discoveries, Simon Marius in Germany claimed to have seen something *'like a candle shining through a horn'*, which we now know as Andromeda galaxy, the neighbouring galaxy of Milky Way. Also, a student of Scheiner (who had observed sunspots) discovered that one of the stars in Orion constellation was not a star, but a luminous patch, which we now know as the Orion Nebula. Those were the beginnings, and astronomers in the eighteenth century would build on these discoveries, and vastly increase the limits of what one could study sitting on Earth.

4

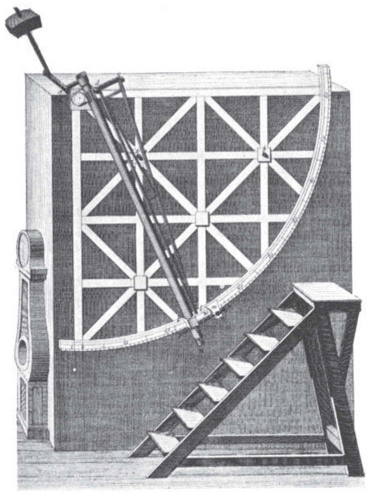
Beyond the solar system: 18th century telescopes

The beginning of the 18th century witnessed significant development in the building of large reflecting telescopes. When Newton built his first telescope in 1670, he had realised its disadvantages, along with the advantages over refracting telescopes. Firstly, it was difficult to fashion the surface of mirrors to good accuracy. As a matter of fact, the mirror surface needed to be many times more accurately polished and ground than a lens of the same size for the same image quality. If a reflecting telescope with a 10-centimeter diameter mirror was to produce a star image that was an arc second across, then the sum of errors in the surface quality of two mirrors should not exceed approximately a tenth of the wavelength of visible light, which is a millionth of a millimetre. One could polish only hard metals to that accuracy, and the best reflecting metals like tin and silver were *not* hard. Stainless steel was not available then. Also, one did not know how to silver glass mirrors properly.

Growth of reflecting telescopes

Newton had used an alloy of copper and tin and other 'speculum' metals, which produced fairly hard and reflecting surfaces. The reflecting quality was still very low: only about half of the incident light was reflected. Also, the copper in the mirror was tarnished and became blackish-brown with time.

In 1720, Edmund Halley took over the Greenwich observatory as the Royal Astronomer, and found to his dismay that Flamsteed's heirs had removed the instruments Flamsteed had installed. First he built a 1.5-metre long reflecting telescope, which was used for observations of transit of stars across the north-south line in the sky, and to which a precision scale was added. Then he installed a mural quadrant, fitted with a refracting telescope of diameter 3.5-centimetre.



HALLEY'S QUADRANT.
(*From an old print.*)

Figure 22: The mural quadrant commissioned by Halley gave a spurt to the making of precise instruments in the 18th century.

A mural quadrant is essentially a device to measure angles in the sky, mounted on a wall which is usually built along the north-south line. Ancient mural instruments, like that in the Samarkand observatory of Ulugh Beg, were built into the wall. Tycho Brahe's observatory was also equipped with a mural instrument. Subsequently, astronomers began to use a frame mounted on a wall, with an arc which was graduated, and an instrument like a telescope was fitted to point at celestial objects and record the angle. The bigger the arc, the finer would be the measurement. In Halley's quadrant, which had a radius of 2.5-metre, the difference of eight arc seconds amounted to a displacement of 0.1 millimetre, and so his instrument had an accuracy of about a few arc seconds.

There were many sources of errors though. There was the distortion of the telescope due to flexure under its own weight, as well as the warping of the frame over time. Halley made sure that the wall was built on firm ground (since an earlier quadrant made during Flamsteed's time had sunk and tipped by over a degree, making all observations with it obsolete). And this quadrant became the model of many such instruments that were built in the 18th century.

Figure 23: A reflecting telescope built by James Short, using the Gregorian design. A 'finder' telescope, mounted on top of the main tube, was used to point the tube in the right direction.

The quadrants were not always used for astronomical purpose though. In the mid-18th century, it was also used to measure the length of a degree of latitude on the surface of Earth. Observations near the equator by Pierre Bouguer and in the north of Lapland by Pierre de Maupertuis showed that the Earth was a flattened sphere— the equator bulged outwards slightly, because of Earth's rotation. Newton had predicted it on the basis of his theory of gravitation and these observations proved him correct.

Halley then set about to build larger reflecting telescopes. In 1721, John Hadley built a telescope with metallic mirrors, with a primary of 15 centimetres in diameter. It was found to be better than a 20-cm aperture refracting telescope, and of course it was easier to handle. Hadley's telescope encouraged Molyneux and Bradley (who had found the first observational proof of Earth's rotation from stellar aberration) to turn their attention to experimentation with metal alloys to find a good reflector. An optimum amount of copper was to be used in the alloy; too much of it made the surface tarnish quickly, and too little made the metal brittle and impossible to cast. Newton had suggested adding arsenic, but it had a boiling temperature lower than that of copper and so the alloying process could not be controlled well. Molyneux settled on a mixture of bronze and brass, that is a copper-tin-zinc alloy, and communicated his results to Hadley.

Soon there were commercial telescope makers in the market. Francis Hawksbee of London and Passemant in Paris, among others, began to build telescopes to sell. James Short of Edinburgh became famous for making precision instruments, mostly reflecting telescopes with a Gregorian design (which needed precise alignments), and made thousands of small telescopes. These were not only for wealthy dabblers in science, but also for professional astronomers to use. Short supplied a 24-cm aperture reflecting telescope to the Greenwich observatory, where astronomers used it to study the eclipses of Jupiter's moons, for which they needed good quality images, and therefore, well polished mirrors.

Sizing up the solar system

There were two major astronomical events during this time: two transits of Venus in front of the disc of the Sun in 1761 and 1769. Halley had carefully selected a few sites from where these events could be observed best. He knew the importance of these events. The transit of Venus would help astronomers accurately measure the distance of the Sun from Earth, and therefore have an accurate idea of the size of the solar system. So far, astronomers had estimated the size of Venus's orbit by parallax, and that too pushing their instruments to the edge of their limits.

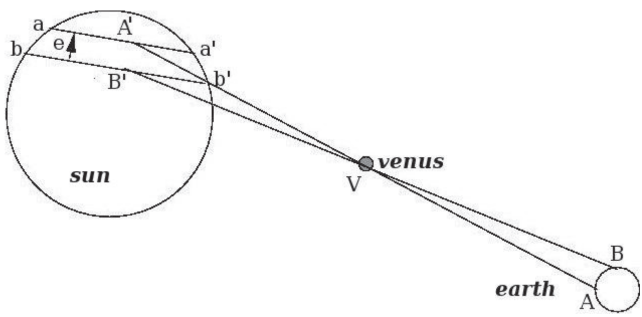


Figure 24: Halley argued that observing the transit of Venus from different places (A & B) on the Earth would provide an accurate distance of the Sun from the Earth. Observers at A & B would see Venus cross the disc of the Sun along the arcs aA'a' and bB'b', respectively, the distance between which (e) depends on the distances between Earth, Sun, and Venus, and the distance AB on Earth. With observations from a number of points on Earth, one can determine the distance between the Earth and the Sun[1].

[1] The ratio between e and AB is known to be about 2.6 (from the ratio of periods of revolutions of Earth and Venus, using Kepler's third law). Then, pooling all the transit observations, one determines the ratio between e and the diameter of the Sun. Knowing the solar diameter, one can determine the distance from Earth from its angular diameter observed on Earth.

During a transit, the distance between the Earth and the Sun could be measured by the different times the silhouette of Venus took to cross the disc of the Sun, as seen from different latitudes (Figure 24).

The 1769 transit was observed by 151 astronomers at 77 different stations around the world. Among them was an expedition led by James Cook, to observe the transit of Venus at Tahiti, at a port that was later christened Port Venus[2].

Astronomers calculated the Earth-Sun distance to be between 143 and 150 million kilometres from their combined observations. But more than that, these events encouraged a young man make a significant advance in the making of telescopes. William Herschel was an organist at a chapel in Bath, England, who gave music lessons in his free time. In 1773, Herschel began to study astronomy at the age of 35, and to tinker with lenses and mirrors. In a few months' time, he had built a 60-cm long reflector, saw Saturn's rings and the Orion nebula and was consumed by his new passion, in whose pursuit he was ably aided by his sister Caroline. His days were spent in music and polishing of mirrors and the nights he spent in observing the sky. In 1777, he began to write a review of Flamsteed's catalogue.

A map of the Milky Way

In March 1781, while surveying the sky, he noticed a faint object in the Gemini constellation, which seemed to move

[2] Astronomers had also come to India for this purpose. Guillaume le Gentil from France had come to Pondicherry in 1761, but by the time he arrived the town was captured by British forces, while he waited in the Indian Ocean for news. Having failed to see the transit, he decided to wait until 1769 for the next transit. But the day of the transit turned out to be cloudy in Pondicherry.

slowly from night to night. Herschel's telescope was far superior to anyone else's, and even when Herschel alerted others, no one could spot it in their telescope. The professional astronomers were befuddled by the ingenuity of an amateur like Herschel, and the discovery of a 'comet' was published by the Royal Society. It turned out to be not a comet though, but a planet whose orbit was twice as large as that of Saturn around the Sun.

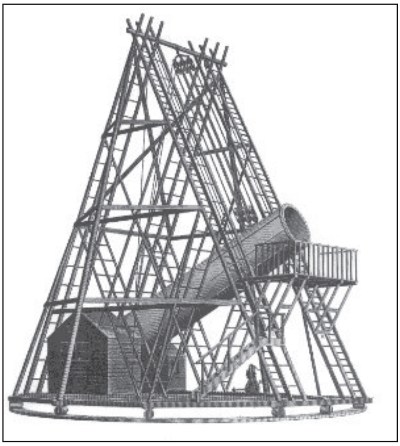


Figure 25: The 40-foot telescope used by Herschel.

Herschel had not only discovered a new planet in the solar system, but could also estimate its size from the angular extent of its image (five arc seconds in his telescope). It was a giant planet indeed, the third biggest in the solar system. It was named Uranus, after the name of Saturn's father in mythology.

Herschel was invited by the King George III to bring his telescope and show, and Herschel wasted no time in asking the king for financial support of his astronomical work. He was appointed the Royal Astronomer, and his official duty was to show members of the royal family views of the sky through his telescope! His salary was less than what he earned as a musician, but Herschel left everything else to pursue astronomy.

He began to study a list of objects that Charles Messier in Paris had made. Messier was interested in comets, but was often distracted by objects in the sky that appeared blurred but were not comets, because they did not move. He made up a list of all those diffuse and stationary objects in the sky, so that he could avoid them in his study of comets. Astronomers still refer to objects in this list with Messier's catalogue number, prefixed by the letter M for Messier. For example, Andromeda galaxy was the 31st entry in his catalogue, so it is denoted as M31. Herschel found that he could resolve the blurred objects in Messier's catalogue into clusters of stars.

Then he made a hypothesis. Suppose our Sun was *inside* a star cluster. What would it look like from outside? Were the stars distributed as though in a sphere, or did it have a different shape. To investigate this, he sought to study the variation of number of stars in different directions of the sky. His motivation was to find out the distribution of stars around the Earth, and how the world of stars looked from outside and not as it appeared to someone sitting inside it.

This study led to his drawing up a 'map' of the universe. Herschel thought he could explain the appearance of Milky Way by imagining it to be a collection of stars in a flat disc: one sees many stars when one looks in the plane of the disc, and few stars while looking out of the disc. He made a working assumption that all stars were equally bright and

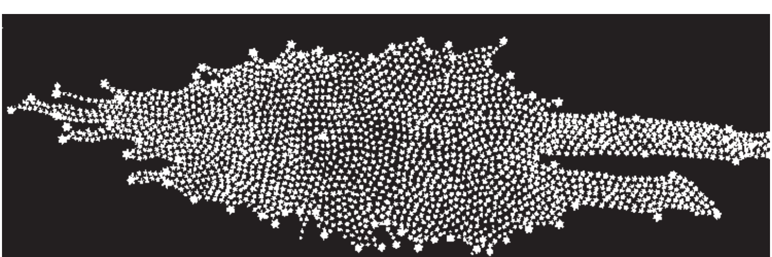


Figure 26: The Milky Way according to Herschel.

therefore estimate the distances of stars by their brightness, and then make a 'map' of the Milky Way (Figure 26). His assumption of equal brightness was of course simplistic, but it was still a giant leap for astronomers.

All these observations were done with Caroline's help, with her sitting at the foot of the telescope, taking notes. Herschel also built and sold telescopes to supplement his meagre salary[3]. Observing was not easy either. Once during the freezing winter of 1783, Caroline slipped while trying to move a snow-covered 6-metre telescope in the darkness, and they looked for a drier place to work, finally moving to Slough. In 1785, he started building a 1.2-metre aperture and 12 metre (40 feet) long telescope with the aid of a grant from the King— the biggest at that time in the world. The mirror was cast by a professional founder from London and it weighed half a ton. Grinding and polishing took many years, and in the meantime Herschel developed a machine for grinding. Finally it was ready in 1789, and almost immediately (on the second night of observing), Herschel discovered the sixth satellite of Saturn.

The giant telescope was unwieldy to operate, and the humid climate of Slough did not allow Herschel to observe more than a hundred hours a year. Moreover, the mirror had a rather high copper content, and it tarnished quickly. Most of Herschel's observations were still being done by the old 6-metre (20 feet) telescope. But what Herschel discovered in the next quarter of a century was anything but a champion's feat. While Caroline discovered several new comets, he discovered a seventh moon of Saturn, corrected Flamsteed's catalogue, as well as discovered many

[3] To give an idea of the price of a telescope at that time: he sold a 2-metre telescope at £ 65 in 1785.

stars which varied their brightness (variable stars). In 1811 he discovered that some diffuse objects did not quite resolve into separate stars, but were truly diffuse. This was an indication (although no proof) that the space between the stars was not empty, but there was diffuse (and glowing) gas in it.

He made a remarkable discovery in 1800, while studying the sunlight with the help of different filters (of different colours). He found that red light heated more than yellow and green, and also that there was an 'invisible light' beyond the red, which followed the usual rules of optics, and heated more than the red. This is what we now call 'infra-red' light, and its discovery was a harbinger of modern astrophysics in the next century, as we shall see in the next chapters.

Herschel also proved that Sun must be *moving* within the Milky Way. When we move, the appearance of objects around changes as a result of our motion: objects in front move towards the sides, and things from the sides appear to move backward and crowd behind our back. From an analysis of the motions of stars around us over time, Herschel concluded that the Sun must be moving toward a point that lay towards the constellation of Hercules in the sky. So less than a century after astronomers proved that the Earth was moving through space, they had also found out the motion of the Sun.

Herschel's fifty-year long research in astronomy epitomized what science could achieve with the combination of good instruments and unprejudiced interpretation. His research took mankind not only to the outer realms of solar system, but gave a peek at the possible structure of our Galaxy, the Milky Way, and our motion within it. This combination would be seen to pay off repeatedly in the next couple of centuries. Better and bigger telescopes always produced new and startling discoveries, stretching the horizon of our knowledge by another notch, and the advancement on the theoretical front would help scientists to understand these discoveries and prod them to build even bigger instruments to test the predictions of these theories.

Science has always progressed thus: better experiments lead to improved theories, and then to test the predictions of these theories, one builds even better instruments, and so on. The history of astronomy can thus be marked by the coming of bigger telescopes which have prompted theoreticians to improve upon their theories, and theorists prompting observers to build bigger telescopes to further test their predictions.

5

The birth of astrophysics: 19th century

Working on telescopes led to many interesting developments in the theoretical ideas of light in the 18th and 19th century. Among other things, Newton's criticism of refracting telescopes led to a vigorous study of chromatic aberration in particular, and theory of light in general. The study of colours also led to spectroscopy in the 19th century and gave birth to astrophysics, the study of the physics and chemistry of the material that celestial objects were made of.

Newton's obituary of refracting telescope, however, turned out to be quite premature. He had thought that all material with same average refracting power (i.e., with the same mean refractive index), would also disperse the colours equally. He therefore thought that the problem of lenses not being able to bring all colours into the same focus could not be remedied. Refracting telescopes were, according to him, doomed to show coloured halos around their images.

Re-birth of refracting telescopes

Although Newton's ideas were dominant in the 17th century, fortunately there were a few dissenting voices. Huygens had criticised Newton's idea that light was made of particles, and developed the idea of light as waves. Leonhard Euler, a mathematician, supported the wave theory. He also wrote a paper suggesting that one could build a two-component lens with water between them that might make the combination colour free.

These speculations were proved correct by Chester Moor Hall. He experimented with two types of glasses: crown glass that people used to make windows and spectacles, and flint glass that glass makers were making at that time for tableware and chandeliers, in which a bit of lead oxide was added to make it heavy. Then John Dollond showed that a combination of lenses was indeed capable of overcoming the effects of chromatic aberration, and he got a patent on it in 1758. Soon, better achromatic lens designs arrived on the scene, and by the time of the Venus transit in 1769, twenty-seven of the 150 telescopes that observed it were fitted with achromatic lenses[1].

After Dollond, Jesse Ramsden built a number of telescopes with achromatic lenses. He was a great instrument manufacturer. One of his major inventions was developing a screw thread, with which accurate measurements could be done. He devoted fifteen years to make a machine so that one could make a screw thread whose helix was accurate to within ten microns (0.001 millimetres). This was used in a dividing engine, a machine for engraving the accurate scales needed on angle-measuring devices needed in astronomy and navigation. Ramsden was a careful engineer and it took several years, sometimes decades, for him to build telescopes.

Guiseppi Piazzi of Palermo, Italy, wanted him to build a 1.5-metre focal length refractor, and virtually laid siege to Ramsden's house in order to get it built quickly. When the telescope was finally installed atop the royal palace in Palermo, Piazzi immediately discovered that the so called fixed stars moved more often than previously thought. The

[1] Flint glass was not easy to make, and it restricted the size of the refractors in which achromatic lenses could be fit, but these advances led to the better terrestrial telescopes.

Pole star moved 1/3 of an arc second every year— it would have been impossible to detect this motion without the aid of a precise instrument.

In 1801, Piazzi discovered Ceres, then called a minor planet (and now called a dwarf planet, in the same category as Pluto), and its orbit lay between that of Mars and Jupiter. Incidentally, Johann Bode of the Berlin Observatory had a theory of planetary distances, and had written to Piazzi to look for a planet between Mars and Jupiter where he predicted a planet. (This relation among the planetary distances still remains unexplained, and is called the Titius-Bode law.) Piazzi had discovered Ceres before the letter arrived.

At the time of Ramsden's death in the year 1800, the glass industry in England went through a period of decline. Heavy taxes were levied on glass, which was seen as a sign of wealth, and since the tax depended on the weight of the glass, manufacturers stopped making heavy lead glasses that were crucial for astronomy. It took several years before the government realised the mistake and reduced the taxes. Elsewhere in the continent, glass manufacturers faced problems of a different kind. They could not make large lenses because it was difficult to keep the mixture of the melt uniform. In low temperature furnaces, the molten mixture of sand, potash and lead oxide remained viscous and trapped air bubbles that formed from the air in the original mixture. In hot furnaces, the melt was less viscous and the heavy lead oxide sank to the bottom, making the mixture non-uniform. The problem was to find a suitable stirrer for the viscous raw glass. Iron rod stirrers lead to traces of iron in glass and made it brown, and inert rods made of fireclay were not strong enough.

This problem was solved by a Swiss carpenter named Pierre Guinand who took an interest in casting bells. He found that a fireclay tube with an iron rod inside was the best solution. He kept his technique a secret and began to make high quality flint glass. He moved to Munich and chose an assistant named Joseph Fraunhofer who would revolutionise the science of astronomy in future.

Measuring the spectrum

Soon Fraunhofer invented a device that could measure the deviation of light rays of different colours with a graduated scale; he had built the first 'spectroscope'. It was not enough to discuss the 'colour' of light, since colour is subjective to a large extent. How does one distinguish the subtle hues and shades between related colours? To be able to do better science, one needed to quantify the colour in terms of the wavelength of the light ray. Fraunhofer could measure the angle of deviation of light rays of different colours, and thereby quantify its 'colour'.

In 1814, he discovered something extraordinary with this new instrument. He found that the spectrum of the Sun was not a simple colourful band, but consisted of many dark lines superposed on it. With his angle-measuring instrument he found that the angles at which the lines occurred were always the same. He labelled the lines with letters of the alphabet, beginning with A (in red) which was the strongest, then B, C and so on, to H at the other end at violet. These 'lines' were later shown to arise due to the existence of different elements in the Sun.

Figure 27: The dark lines in the spectrum of the Sun that are known as Fraunhofer lines (postage stamp of Germany: 1987).

Fraunhofer continued to build telescopes, and his masterpiece was a 24-cm aperture refractor made for the Dorpat Observatory in today's Estonia that he completed in 1826. This big telescope had two lead weights near the eyepiece to minimise the bending of the telescope tube. Fraunhofer also made a 16-cm telescope for Friedrich Bessel of Konigsberg, Germany, who used it to study a particular pair of stars, listed in Flamsteed's catalogue as No. 61 in Cygnus constellation, and therefore called 61 Cygni. Piazzi had observed this pair of stars and found them moving across the sky at a rather high speed. Bessel confirmed the high speed and wondered if it was due to the fact that these stars were close to the Earth— opposite to Herschel's assumption that only bright stars were nearby (since he assumed all stars to be of equal intrinsic brightness).

Then in 1838, Bessel measured the parallax of 61 Cygni: over the span of a year, it appeared to move by as much as 0.676 arc second. This implied that the star was roughly 100,000,000,000,000 kilometres away— more than thirty thousand times farther away than the farthest planet known then, Uranus. Astronomers devised a unit of distance based on parallax: stars that cause a shift of one arc second over a year are at a distance of one 'parsec', which is roughly 3 light years. Measured in this unit, the distance of 61 Cygni was about 3.5 parsecs, or about 11 light years.

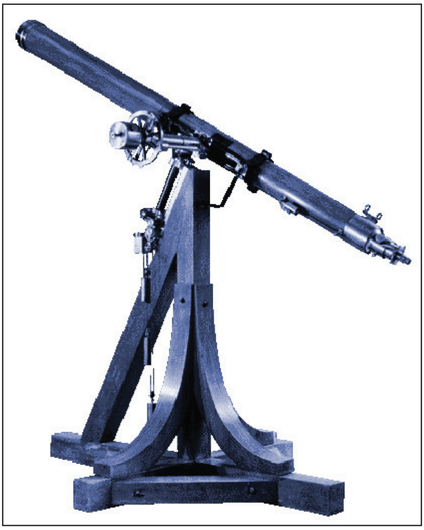


Figure 28: The 'Dorpat' telescope built by Fraunhofer.

This was the first measurement of the distance to a star, and the quest for determining stellar distances from parallax, beginning with Copernicus, had finally been successful. Soon thereafter, F. G. W. Struve used the Dorpat telescope built by Fraunhofer to find the distance to the bright star Vega, and Thomas Henderson measured the distance to Alpha Centauri.

These measurements were a silent victory for the refractors: Herschel's reflector had greater resolving power, but the refractors built by Fraunhofer had the stability needed for parallax measurements. Alpha Centauri was found to be at a distance of 4.3 light years, and no other star was found nearer than this. It was the closest star to solar system. Astronomers realised that our Galaxy, of which the Sun was a component, was mostly empty. The nearest hundred stars occupied a space that was roughly 40 light years in diameter!

Struve found that the pairs of stars he studied had orbits around each other that obeyed Kepler's laws for planets in the solar system. Newton had called his law of gravitation 'universal', and now astronomers increased the range of its validity to the known edge of the cosmos. In ten years' time, Bessel made another startling discovery using Fraunhofer's telescope. He studied the bright star Sirius and found its path wobble across the sky, and inferred the existence of a dim companion whose gravitational pull made Sirius wobble in space. He even estimated its mass, and from the dimness implied by the fact that companion was invisible, it was judged a strange star indeed. (Much later, this star would be shown to be a white dwarf, a compact star that forms out of the core of a normal star like the Sun.)

Large reflectors

In the early nineteenth century, the glory of reflectors was eclipsed for a while. In 1833, John Herschel, son of William Herschel, took his father's 47-cm aperture reflector to South Africa, to study the nebulae and star clusters visible only in the Southern Hemisphere. Another big reflector (38-cm aperture) was made by John Ramage of Scotland and was installed at Greenwich. These were the largest reflectors of that time, but astronomers seemed to prefer smaller refractors fitted with achromatic lenses. (It was around this time that telescopes were named after the size of the aperture and not their lengths, a convention still being followed.)

Then came an Irishman, William Parsons, who began to build large reflectors, reminiscent of Herschel's era. He came from a wealthy family, went into politics after studying mathematics at Oxford, and became the third Earl of Rosse. He had become interested in telescopes. The biggest problem in making reflectors those days was the fact the copper-tin

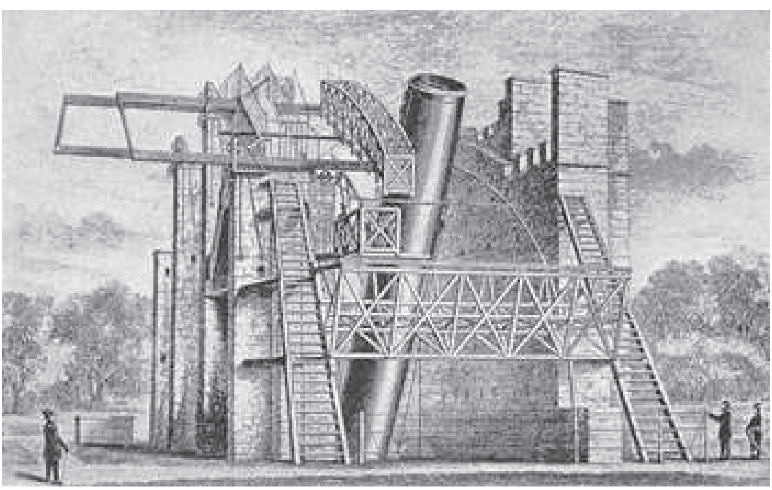


Figure 29: The 180-centimetre (72inch) 'Leviathan' telescope of Lord Rosse.

alloy was brittle. Herschel had to use more than optimum amount of copper to make it less brittle but it made it less reflective. In the 1830s, Lord Rosse experimented with small pieces of this alloy, and made a 60-centimetre mosaic mirror that was ground and polished on a steam-driven machine. It was a success, and Lord Rosse abandoned his seat in the Parliament and began to make a 90-cm reflector.

By 1840, he had finished a mosaic of smaller pieces that he needed to join in order to make the large mirror. But the joins between the pieces affected the polishing process and the image was not very sharp. Then he abandoned the idea of mosaics, and tried to cast a monolithic 90-cm mirror, using a very complex procedure that took fourteen days to cast the mirror. Finally, in 1845, he was successful and was able to build a mirror that was better in optical quality than Herschel's mirror. Lord Rosse was so enthusiastic that he planned to build a bigger telescope, a 180-cm giant of a telescope. By now he had mastered the process and it was built quickly: he finished building it in 1845 (just before the potato famine broke in Ireland, after which Lord Rosse would have to devote more time to famine relief than astronomy). They called it the 'Leviathan of Parsonstown'. The mirror weighed four tonnes, and was supported by a system of pads and levers to minimise the distortion under its own weight. It was however slung between two walls and restricted its field of view: stars could not be observed for more than an hour at a stretch. Also, the weather around Birr Castle was terrible. Yet, in the rare cases of clear nights, the telescope gave the finest images ever of the distant objects. It was able to separate images of stars that were separated by only half an arc second. Many double stars, which had earlier appeared to be a blurred single image, were 'resolved'.

With the new telescope, Lord Rosse sketched what he saw. He discovered that some 'nebulae' showed spiral arms.

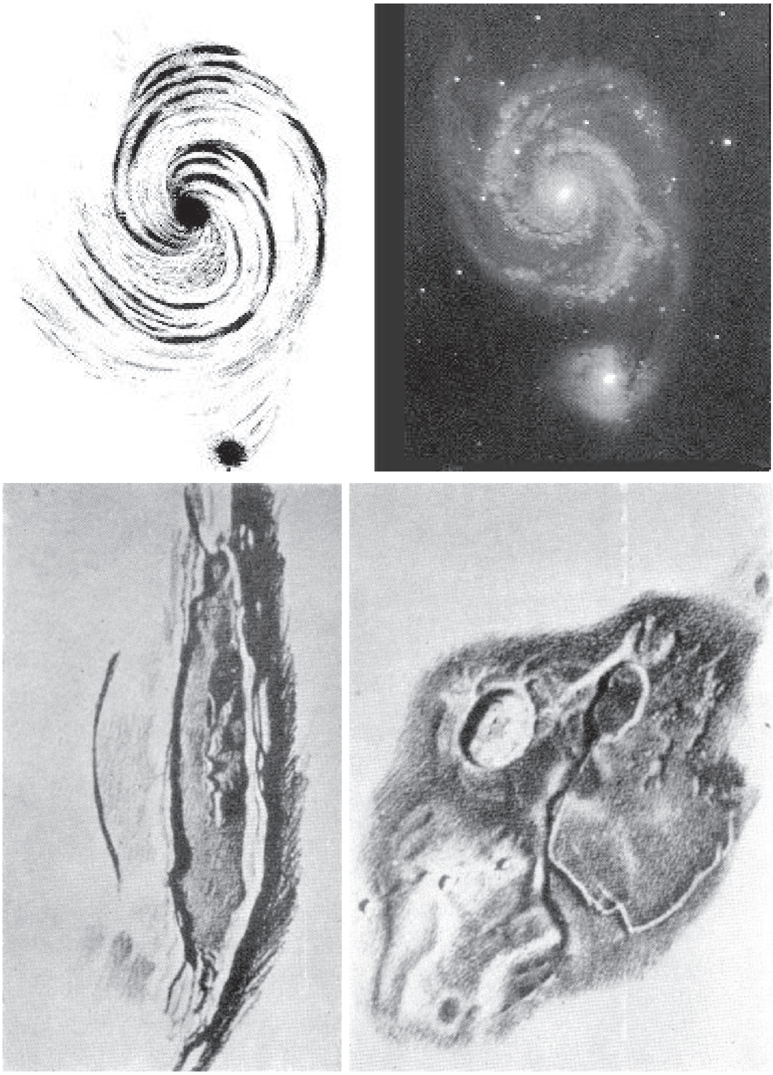


Figure 30: Lord Rosse's sketch of a spiral galaxy, M51, and its image through a modern telescope. His sketch of two craters on the Moon (Humboldt and Aristarchus) is shown on the right.

Today we know them as galaxies not only outside of Milky Way, but much distant from it.

At around the same time, two other amateurs were also building large reflectors. James Nasmyth, a Scottish engineer, built a 50-cm telescope on equatorial mounting, and William Lassell, an English brewer, built a 60-cm telescope in 1846. There was a dramatic development that year leading to the discovery of Neptune on 23rd September. It was discovered at the Berlin observatory after two theorists, John Adams from England and Urbain Le Verrier from France predicted its position based on their work on the orbit of Uranus. Astronomers had noticed that Uranus swayed from its orbit, which they thought was due to the tug of a yet unseen object. Adams and Le Verrier considered a hypothetical planet beyond Uranus which could alter its movements by gravitational pull. After the news of the discovery of Neptune, Lassell observed it with his new reflector and even discovered a satellite (Triton) of Neptune.

Photography with telescopes

The discovery of Neptune involved searching for a moving object among the distant stars in the field of view of the telescope. Astronomers painstakingly noted the position of every object in the field of view and compared these with their positions after some time or after a night. This procedure would dramatically change with the advent of a remarkable discovery— that of photography.

Scientists in the 18th century had noted that many silver compounds like silver chloride were blackened by sunlight, when minute particles of metallic silver formed (which appeared dark compared to the white colour of silver chloride). Therefore, it was possible to make a silhouette of an opaque object by allowing its shadow to fall on paper sprayed with silver chloride.

The first experiments did not produce any 'image' because it took a long time, sometimes hours, to blacken even by a small amount. Then Joseph Niépce discovered that sunlight rendered bitumen insoluble. He focussed the image (from a camera) to fall on a thin layer of bitumen deposited on a pewter plate: wherever the sunlight fell sufficiently, the bitumen became insoluble, and Niépce washed the plate to remove the still soluble parts, and so he had a 'fixed' image. It however took roughly ten hours of exposure to produce it. Then in 1835, Louis Daguerre found that he could 'develop' by mercury vapour an invisible 'latent' image on a plate that was exposed to an image too weak to produce a visible blackening. It allowed him to cut down the exposure time to twenty minutes, and in two years' time, Daguerre found a way of 'fixing' the developed image by washing with a strong solution of common salt.

He tried out the first experiment of taking a photograph of the Moon with the telescopes at the Paris Observatory in 1839, but the result was too blurry to be of any use. The first success in astronomical photography came a year after, on the other side of the world. John Draper, a chemistry professor at New York, managed to photograph the Moon in 1840, with a twenty minute exposure. Then the exposure time was brought down to minutes by using silver plates sensitized with iodine-bromine or iodine-chlorine mixtures. In 1851, astronomers at the Konigsberg Observatory photographed the corona of the Sun during a solar eclipse.

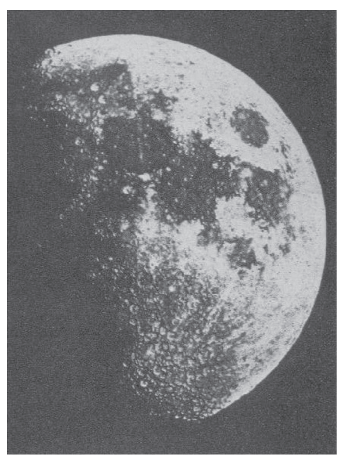


Figure 31: A photograph of the Moon by Warren de la Rue in 1865.

Astronomical photography was taken another step forward by an invention in 1850 by Frederick Archer, who used glass plates coated with a thin film of collodion (gun cotton). Warren de la Rue, an amateur and a friend of Nasmyth and Lassell, built a 33-centimetre telescope and tried Archer's method to take photographs of the Moon. It was a remarkably good image, given the fact that the telescope did not have any drive to track the Moon in the sky, and de la Rue had to guide it with his hand.

By 1865, astronomers could take photographs of stars invisible to the naked eye. Lewis Rutherford of New York built a telescope fitted with a lens that was photographically achromatic. The ordinary 'visual' achromatic lenses brought mostly green to orange lights at the focus, because the eye is not sensitive to violet rays. But for photography, one had to build achromatic lenses that brought violet to red rays at the same focus. Rutherford's images not only had a good accuracy, but being a permanent image, they had the advantage of being measured at any time later on.

Spectra of stars

Observational astronomy entered yet another phase when spectroscopy was developed. After the discovery of 'dark lines' in the spectrum of the Sun by Fraunhofer, scientists found the spectrum of light emitted by burning different objects. They studied with their spectroscope the light from flames of different gases, and from hot objects like a lump of coal or iron. Slowly it was understood that there were two types of spectra. One type of spectrum was a continuous band of colours from light emitted by hot objects, and another was a complex mixture of bright and dark lines, that arose from sources like flames and sparks.

By this time, the wave nature of light was firmly established. Thomas Young had shown in 1801 that light rays emerging from two adjacent slits could combine in a way only possible for waves: the wave amplitude was enhanced in some places and annulled at other places, giving rise to a band of bright and dark lines. The spectrum of light was then explained by assuming that light consisted of waves of different wavelengths (or frequency), and colour was related to the wavelength. Red light had a wavelength of about 750 nanometres (nm) and violet light, about 400 nm.

Some light sources emitted light at a few distinct wavelengths. For example, the spectrum of a flame that was coloured by adding common salt showed two closely spaced bright yellow lines (589.0 and 589.6 nm). All objects appeared to have a completely different spectrum, and so one could identify an element by studying its spectrum: a spectrum was like the 'fingerprint' of the element.

David Brewster made a crucial discovery at this point of time. He found that a tube filled with nitric oxide gas in front of a hot solid absorbed the light from the hot solid at many wavelengths, and produced 'dark lines'. Therefore the dark lines in the solar spectrum that Fraunhofer had discovered came from cool gas in front of the source of the white light in the Sun. Brewster further found that some of the Fraunhofer lines, e.g., the strong lines labelled A and B, were darker (stronger) at sunset, while other lines remained of the same strength throughout the day. He argued that the Fraunhofer lines A and B must be due to absorption by Earth's atmosphere and the rest were due to absorption by cool gas at the outer surface of the Sun itself.

Astronomers began to take photographs of the Sun's spectrum and did not have to depend on sunlight to study

the Fraunhofer lines anymore— they could study it at leisure after taking its photograph. Finally Gustav Kirchoff came up with an explanation of the Fraunhofer

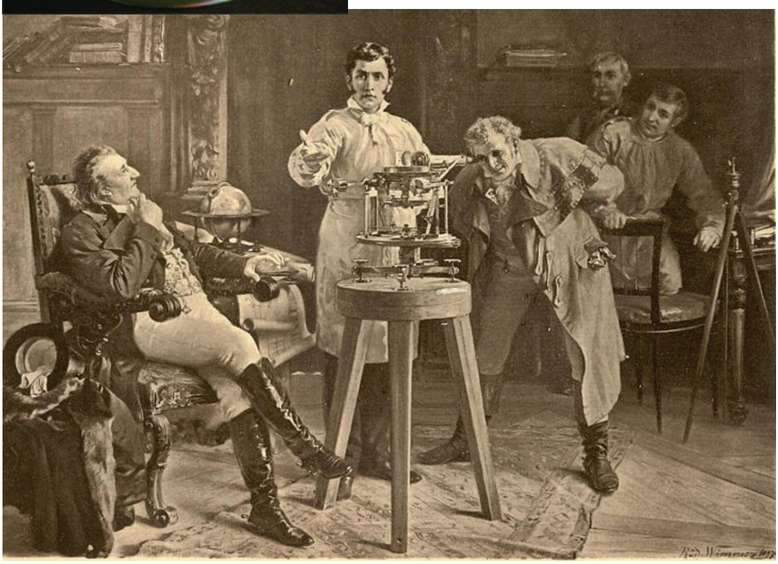


Figure 32: The fine grooves on a compact disc (top) disperse light showing its spectrum. This is an example of how 'diffraction grating', a set of finely spaced lines etched on an optical surface, can be used to produce spectrum of light falling on it. Fraunhofer pioneered the use of diffraction grating, and Angstrom used it extensively in his study of the Fraunhofer lines. The picture at bottom shows Fraunhofer explaining his spectroscope (which used a prism as the disperser of light).

lines. Kirchoff worked with a colleague, Robert Bunsen, at Heidelberg, and they experimented with a series of elements and their spectrum when they were hot and also put these elements in their cold state in front of a light source. They found that every element emitted light with a distinct set of wavelengths, and they absorbed at these very wavelengths when put in front of a source of light. So, the elements responsible for the Fraunhofer 'dark lines' could be identified if one had a catalogue of corresponding bright lines emitted by all elements. For example, sodium emitted the two yellow lines at 589.0 and 589.6 nm when it was heated, but it absorbed light of these very wavelengths when put in front of white light and produced 'dark lines' there.

Kirchoff's explanation revolutionised astronomy unlike anything else. It gave astronomers a clue about the material that celestial objects were made of, and they could connect it to the materials studied by chemists and physicists. Gradually, scientists developed a model of the Sun as consisting of a hot, opaque core that emitted continuous spectrum, surrounded by a relatively cooler gaseous envelope which absorbed some of the light from the core and produced the dark lines of Fraunhofer spectrum. Kirchoff concluded from the study of Sun's spectrum that the Sun's atmosphere contained many known elements of the Earth, like sodium, calcium and so on. Soon Anders Ångstrom of Uppsala, Sweden, identified about 800 lines, using diffraction grating instead of prisms. (We still use a unit of wavelength bearing his name: an Ångstrom is 0.1 nm.)

Discovery of helium

During the solar eclipse of 1868 at Guntur, India, Pierre Janssen discovered that storms on the surface of the Sun gave rise to a spectrum with only a few bright lines, most of which belonged to hydrogen. These 'prominences' of the Sun emitted such a bright spectrum that he could observe it even after the eclipse. Around the same time, Norman Lockyer of England also discovered the phenomenon. Their letters arrived at Paris at the same time and were declared the joint discoverer of the technique. Soon, they found that

Figure 33: Norman Lockyer using a spectroscope attached to a telescope.

there was a bright orange-yellow line that did not correspond to any terrestrial element. This new element was christened 'helium' because it was first discovered in the Sun (and which was called 'helios' in Greek).

Soon astronomers were using spectroscopy to study other stars. William Huggins used a 20-cm refractor with a spectroscope near the eyepiece and studied (and photographed) the spectra of a few bright stars. He also found that the spectrum of a nebula in Draco constellation did not show many dark lines like other stars did, but a single bright line. He concluded that this nebula did not consist of individual stars, but was a cloud of glowing gas. The old debate from Herschel's time could now be set aside— there was indeed diffuse gas in the interstellar space.

Huggins also discovered that at times the set of stellar lines were shifted to the red or blue by a small amount. This was due to the motion of stars, either away from or towards the Earth, and the shift in wavelength was proportional to the speed. Huggins could, therefore, measure the speed of stars and found that they had speeds of tens of kilometres per second.

Angelo Secchi used a small (10-cm) prism at the top end of a 15-cm refractor, so that every star appeared through his eyepiece not as a point but as a small spectrum. Secchi studied about 4,000 stars and discovered that one could classify stars according to their spectra. At one end there were blue-white stars like Vega in Lyra constellation whose spectra were relatively simple, a uniform continuum with few dark lines. At the other end, one had red stars, like Betelgeuse in Orion, whose spectra showed bands of dark absorbers.

Fraunhofer's discovery, the advent of spectroscopy and photography, all worked to change the flavour of astronomy in the first half of the 19th century. Astronomers could now discuss what the celestial objects comprised of and how they moved, and they could relate these celestial phenomena to the laws of physics and chemistry derived from laboratory studies on the Earth. The science of astrophysics was born. Quite appropriately, the epitaph of Fraunhofer at Munich said: '*He brought the stars closer to us*' [2].

2 'Approximaverit Sidera'

6

Telescopes at the end of 19th century

Astronomers after Lord Rosse continued to build bigger telescopes, although it was not always that they made the most interesting discoveries. As a matter of fact, the startling observations made at this time were mostly done by observers with modest size telescopes, although with ingenuous instrumentation: de la Rue had a 9-cm telescope and Huggins had a 20-cm refractor. But one could not deny the advantage of a bigger telescope, and within a decade of Lord Rosse's 'Leviathan' (1.8 metre) telescope, more such telescopes were built, and often with innovations in design that were to stay. And instead of concentrating on spectroscopy, the focus of the observations at the end of the 19th century was measuring the brightness and positions of stars.

Sky maps

Astronomers had by this time achieved considerable progress in determining the positions of stars with high accuracy. The level of accuracy involved is illustrated by the example of Urbain le Verrier's study of the motion of Mercury. Le Verrier found that the long axis of the elliptical orbit of Mercury did not stay fixed in space, but rotated around the Sun with a speed of 5.7 arc seconds a year. (He had to subtract the effect of the precession of Earth's axis to derive this value.) He then estimated the effect of the gravitational pull of planets and it accounted for 5.3 arc seconds a year. The remainder, of 0.4 arc seconds a year was still unexplained (and was later explained by Albert Einstein with the help of a new theory of gravitation in 1920). This is a tiny effect and it is to the credit of 19th century astronomers and their perseverance that they recorded and wondered about this tiny motion of the perihelion of Mercury.

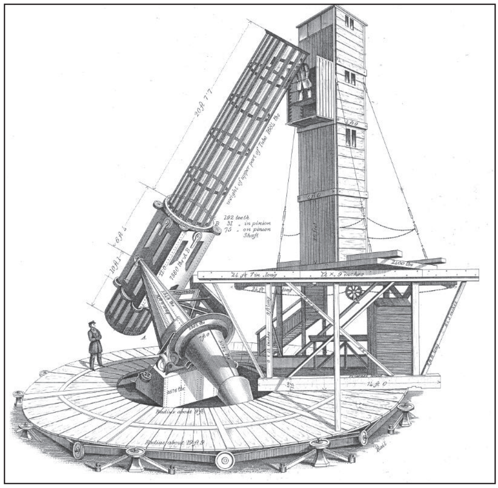


Figure 34: The 1.2-m reflecting telescope built by Lassell and erected at Malta.

Astronomers also became adept at recording the brightness of stars. John Herschel at the Cape of Good Hope devised a crude 'photometer' that used a small lens, a prism and a string to produce a tiny image of the Moon, whose brightness he varied to match the star under observation. Norman Pogson, an astronomer at the Madras Observatory produced a catalogue of more than 10,000 stars, and devised a system of stellar magnitudes, in which stars barely visible to the naked eye had a magnitude of about +6, and a difference of 5 in the magnitude scale corresponded to a multiplicative factor of 100 in luminosity (the higher the luminosity, the smaller the magnitude). The Bonn observatory made a catalogue of 324,000 stars in 1859 that came to be extensively used.

To supplement the observations for stars in the northern sky with those in the southern sky, Lassell built a 1.2 metre telescope at Malta in 1861. Observations were done at the Newtonian focus, and it had a fork-like equatorial mount.

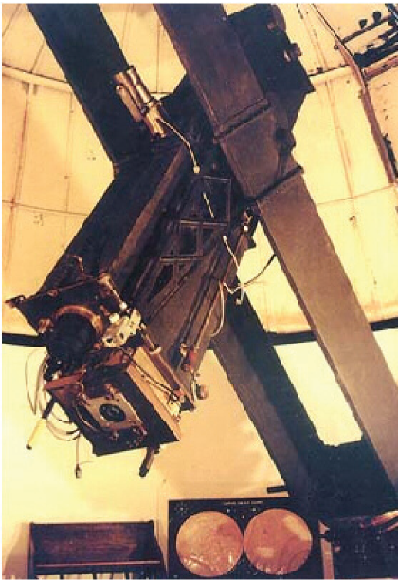


Figure 35: This 33-cm telescope at Toulouse was used to make a comprehensive map of the sky in 1890.

The results were not very encouraging and Lassell abandoned it after three years of observations. Then a plan was drawn up to build another telescope of this size at Melbourne, where convicted labourers could be used for free to build it, but it turned out to be a fiasco. It had a Cassegrain design with a light secondary mirror, but the telescope was very sensitive to flexure and vibration. Even a small motion of the tube greatly distorted the image, and in addition, there was no dome, and the image got distorted even with a slight wind. Moreover, the mirror turned out to be a disaster, as it needed to be re-polished (because they could not remove the shellac coating that was put before shipping).

On the other side of the Atlantic, an erstwhile painter named Alvan Clark dropped his brushes after taking a peek at a 38-cm refracting telescope at Harvard, and turned to making precision lenses. By this time, the tax on glass in England was abolished and the glass industry flourished. Clark made a 47-cm refractor using a glass blank manufactured in England in 1861. It was a telescope of high quality, and showed Sirius as a double star, just as Bessel had predicted. The American Civil War slowed the pace of scientific activity at this point of time though. Years later in

1869, Clark made a 66-cm refractor that was used by Asaph Hall to discover the two faint moons of Mars. Hall later used this telescope again to prove wrong the idea of some astronomers that Mars showed a large network of canal systems. Giovanni Shiaparelli had announced in 1877 that he saw canals on the surface of Mars and that the pattern changed over time, implying the existence of intelligent life on Mars. Observations made with Clark's fine lenses did not quite put an end to these speculations, but they did raise serious doubts.

Mountain-top telescopes

In 1880s a few more large telescopes were built in the USA. The biggest of them, with a 91-cm lens, was again built by Alvan Clark for the Lick Observatory. This was the first big telescope to be put on a high altitude site away from city lights. Then he built a 101-cm refractor which was installed in the Yerkes Observatory near Chicago. These two giant telescopes improved the observations of stellar parallaxes, and astronomers were able to measure distances up to about 200 light years.

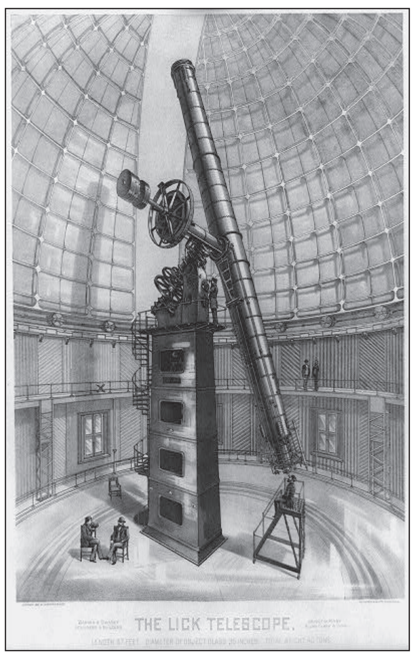


Figure 36: The 91-cm refractor at Lick Observatory.

At the same time, the use of photographic plates made the observations and analysis easier. First they used gelatine-based photographic emulsion, and then by 1879, they began to use dry plates which lasted longer than wet plates, and enabled astronomers to take long exposure pictures, recording faint details. In the early 1880s, European astronomers like Janssen in France had taken detailed photographs of the Orion nebula, and so the artistic ability of observers ceased to be a limiting factor in further analysis of complex astronomical objects. Janssen took a remarkable photograph of the Sun in 1885 that showed granulation on its surface for the first time. Paul and Prosper Henry of Paris took a 3-hour exposure of the Pleiades cluster that showed 1,400 stars (compared to six visible to the naked eye, and 36 seen through Galileo's telescope in 1610). The Henry brothers then began a programme of mapping the sky with a telescope built by Paul Gautier. The photographic plates were then used to measure the positions of stars.

Photographic methods were used in spectroscopy as well. Edward Pickering at Harvard began a series of observations on the line of Secchi before him, with a prism in front of the objective, and made a comprehensive study of about a million stellar spectra. The initial analysis led to a classification into about twenty groups, which were labelled A, B, C, and so on, but subsequent work led to rearrangement of the groups. The final sequence turned out to be O B A F G K M, which is the sequence still in use. O stars are the hottest (and most massive) stars, and M stars are the coolest stars in this series.

Reflectors with glass

Around the middle of the 19th century, a development made metallic reflectors obsolete. It was realised that glass mirrors coated with silver was much better than glass lenses or metallic mirrors. Jean Bernard Léon Foucault of Paris and

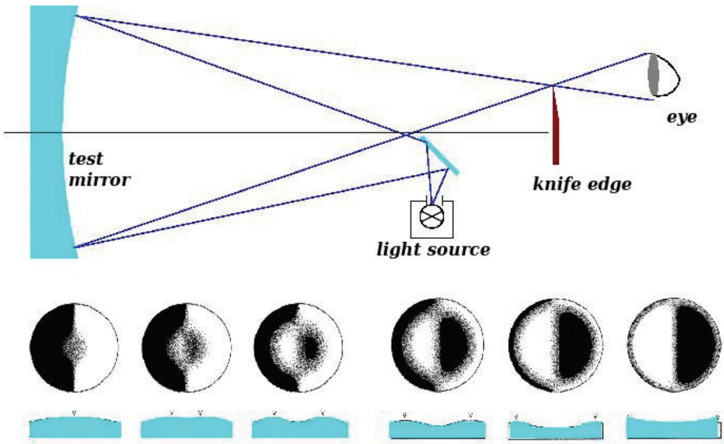


Figure 37: Foucault's test checks the unevenness of mirrors. When a mirror is illuminated by a source of light, and observed behind a knife edge, the pattern of illumination seen by the observer becomes a sensitive test of the geometrical shape of the mirror. The patterns of illumination for a few shapes are shown in the figure.

Karl Steinheil of Munich developed a technique (after being inspired by a demonstration at the Great Exhibition in London in 1851) of producing a uniform, thin and highly reflecting film of silver on glass by chemical means, without losing the surface precision of the glass. Even when this layer was tarnished, a new coating could always be given. Also, glass polishing was much easier than polishing metals.

Foucault built a 33-cm mirror in 1857 for the Paris Observatory, and devised a method of checking the accuracy of the surface (Figure 37). With a simple arrangement involving a light source, a pin hole on an opaque screen and a sharp knife edge, one could measure the unevenness in the mirror surface to an accuracy that was comparable[1] to the wavelength of light (0.5 microns in green).

1 To be precise, the accuracy that was achieved was better than one fourth of the wavelength.

The ill-fated Melbourne reflector was the last of the big reflectors made with metallic mirrors. But the project had taught astronomers and engineers many important lessons on building large telescopes that became useful for modern silver-on-glass telescopes. It was clear that the reflector was sensitive to the effect of misalignment of mirrors and to flexure and vibration of the telescope tube, and also to temperature effects (which gave rise to turbulence in air and degraded the image quality).

It was also clear that a suitable site should be chosen for a telescope, as noted by A. Common who built a 91-cm glass mirror with George Calver. One of his telescopes was brought in 1895 to the Lick observatory in southern California, USA, which was indeed a good site. Using this telescope, J. E. Keeler photographed the Andromeda 'nebula' and discovered spiral arms in it, as well as spiral arms in many other 'nebulae' which were smaller and fainter. It appeared as if they were all alike but at enormous distances from us. Astronomers would soon build telescopes that would settle the question, and therefore increase the size of the observed universe by another notch.

7

Early 20th century telescopes

The new century began with the momentum for big reflectors from the previous years. Refractors were things of the past now: big refractors used lenses so big and thick that they absorbed a lot of incoming light, and they were so heavy that it was not enough to support them only at the edges. In addition, the usual achromats were not really achromatic: the Lick Observatory 91-cm showed a variation of focus of several centimetres between rays of different colours. George Hale, who had helped build the Yerkes observatory earlier, installed in 1908 a 1.5-metre reflector made by George Ritchey on Mount Wilson in southern California, USA. It was so big that its weight was relieved with a mercury float, and with it astronomers initiated a study leading to the understanding of evolution of stars.

The spectral classification of stars had led astronomers to wonder if the sequence of stars from hot to cool surfaces was an *evolutionary* sequence: did stars form hot and blue, and then cool down to become red? Data from the 1.5-m telescope at Mount Wilson made astronomers like Ejner Hertzsprung and Henry Russell realise that this was *not* so. They discovered that most stars fell into a category called the 'main sequence'— for which there was a certain relation between the brightness and surface temperature of stars: hot main sequence stars were bright and red main sequence stars were dim. Apart from these, there were also some giant stars (which were red but bright) and dwarf stars (which were blue but dim).

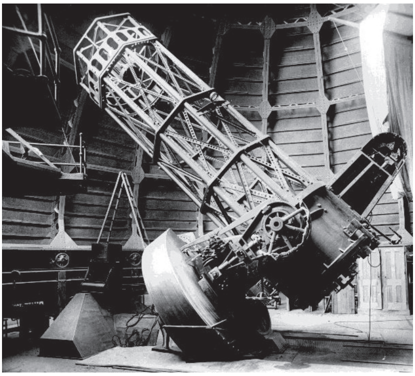


Figure 38: The 1.5-metre telescope at Mount Wilson.

A Dutch astronomer named J. C. Kepteyn used the new 1.5-m telescope data to map the stars in Milky Way, along the lines of William Herschel in the 19th century, but with the new knowledge that there was dust in the interstellar space and that there was interstellar gas, both of which were established in the first decade of the 20th century. Dim stars need not be always distant, as Herschel had assumed; they could be nearby but their light could be dimmed by the intervening gas and dust. The resulting picture of the 'Kepteyn's universe' was a round agglomeration of stars, densely packed in the centre and thinning away outside. Later, Harlow Shapley used this very telescope to argue that our Galaxy was thin and flat, with a radius of 120,000 light years, and also that our Sun was far away from the centre of the Galaxy.

Expansion of the universe

Then arrived the 2.5-metre (100 inch) telescope in 1918, built by J. D. Hooker, a friend of Hale, and installed at Mount Wilson. This telescope was extensively used by Edwin Hubble, who studied distant nebulae with spiral arms. He could determine the distances to these nebulae because the new telescope could resolve individual stars in them, and among these stars he found some stars that belonged to a special category in Pickering's classification of stars. These were Cepheid stars, which pulsated in a regular manner, and Henrietta Leavitt, an assistant of Pickering, had

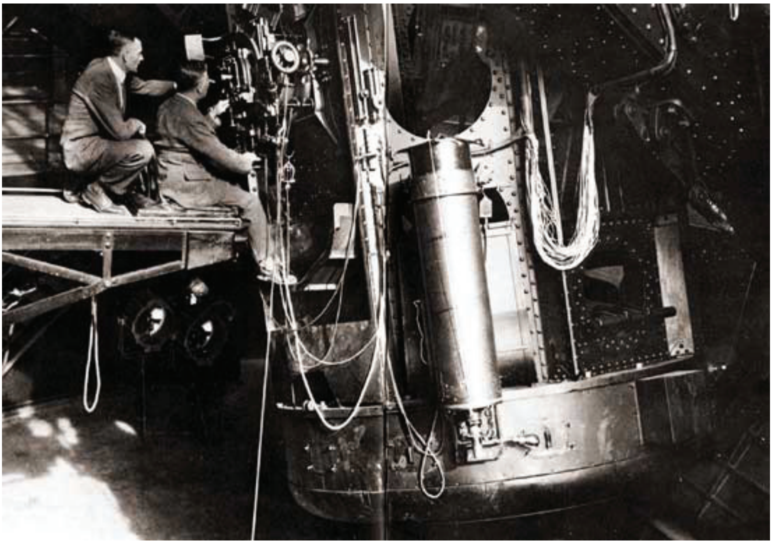


Figure 39: Edwin Hubble at the 2.5-metre telescope with James Jeans.

discovered that *bright* Cepheid stars pulsated *slowly*. So Hubble had to find the pulsating period of Cepheid stars in distant nebulae and then he was able to determine their actual brightness, and therefore, their distances. At the same time, Hubble measured the speed with which these nebulae moved by measuring the shift of their spectral lines against the standard lines from laboratory spectrum.

First he found that the distant nebulae were beyond our Galaxy, the Milky Way. They were a separate collection of stars, and distant from our Galaxy by large distances. Hubble's second discovery (published in 1929) was startling. He found that the *further* a nebula was, the *faster* it moved away from the Earth. Hubble estimated that the faintest nebula in his photographic plate was about 450 million light years away from the Earth, and found them moving away from the Earth with an astounding speed of a thousand kilometres per second. He had discovered the expansion of the universe!

In the following decade, many smaller telescopes were built, and engineers assumed that they had reached the limit of biggest telescopes that could be built with the 2.5-metre. Its mirror weighed a formidable 100 tonne, which had to be relieved by two mercury floats enclosed within two big drums at the two ends of the axis supporting the telescope. Some smaller telescopes were made with innovative designs, like using ball bearings instead of mercury floats, or diverting the reflected beam of light by a third mirror to bend it on to a separate place where a big spectrograph could be placed (which are too big to be put on the telescope itself). This arrangement, called Coudé focus (after the French word for elbow), was used to study magnetic fields on stars among other phenomena (Figure 40).

Gas between the stars

A few smaller telescopes did make important discoveries at this time though. Many astronomers and atomic physicists forged collaborations to understand the atomic spectra and identify elements through spectral lines. Based on these 'laboratory astrophysics' studies, Ira Bowen showed in 1927 that the bright spectral line emanating from gaseous nebula (discovered half a century ago by Huggins) was due to ionised oxygen and nitrogen atoms, under conditions (of high temperature and low density) that were not possible in terrestrial laboratories.

Atoms in high-density regions jostle one another often and de-excite themselves by collisions. If the excited atoms were left alone for a period of time, by some manner, they would have de-excited themselves by emitting radiation. This was only possible in the tenuous regions of interstellar space (and these spectral lines are called 'forbidden lines') where excited atoms are not being disturbed often by collisions. This special type of radiation not only allowed astronomers to view the interstellar gas, but they could also estimate the density and temperature of the interstellar gas by studying its spectrum!

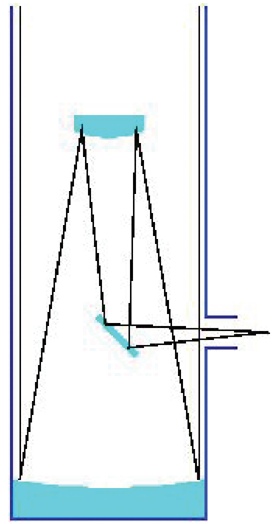


Figure 40: In the Coudé focus arrangement, light rays are diverted by a tertiary mirror to a fixed focus point that does not move even if the orientation of the telescope is changed. This design is often used in large observatories, and allows heavy equipments, such as spectrographs, to be more readily used.

In 1930s, it was found that coating aluminium on glass was a more lasting method than coating silver. Also, a new type of glass was manufactured that was less sensitive to normal glass: pyrex. Since large mirrors took a long time to cool, the temperature dependency of glass was a limiting factor for making large telescopes. These twin discoveries spurred the astronomical community in planning for a bigger telescope. George Hale commissioned a 5-metre (200 inch) telescope, to be installed atop Mount Palomar, and a mirror was cast in 1935, but Hale died in 1938 before seeing the completion of the project. It was later named the Hale telescope in his honour.

While planning for big telescopes, astronomers also wished to view a large portion of the sky at once. Simply pointing a big telescope to a random position or star in the sky would not lead to interesting discoveries: first one had to choose *where* to look, and for this one had to scan a large portion of the sky first. As one made bigger and bigger telescopes, the part of the sky viewed through them became smaller and smaller though. With the 1.5-m telescope at

Mound Wilson it would take about 50 observations to cover the surface of the Moon, which is just a few millionth of the whole sky. A complete survey of the sky would take thousands of years, and so scientists began to think of a new design.

George Ritchey and Henri Chretien came up with an idea to increase the field of view of Cassegrain telescopes. What limits the field of view of a telescope? Usually the image quality is only good for stars whose radiation strikes the telescope along or near the axis of the tube. If the image quality of stars shining at an oblique angle is not good enough, then one is forced to use only the portion of the sky near the axis of the telescope, thereby decreasing the field of view. Ritchey and Chretien changed the primary mirror to a hyperboloid (instead of the usual paraboloid) that was less partial to rays hitting at an oblique angle, and showed that it increased the field of view.

Then Bernard Schmidt of Germany thought he could use a correcting *lens* to correct the faults of a *mirror*, and this increased the field of view as well (Figure 41). His first trial telescope (built in 1930) with an aperture of 36-cm had a field of view of 16 degrees, a vast improvement over other similar sized telescopes. In 1938, F. E. Ross built a corrector lens system to be used for upcoming 5-m Palomar telescope that would give a good image for a field of half a degree across, which would be 200 times the area of the uncorrected system. Then a 1.2-m Schmidt telescope was installed in 1950s to do a

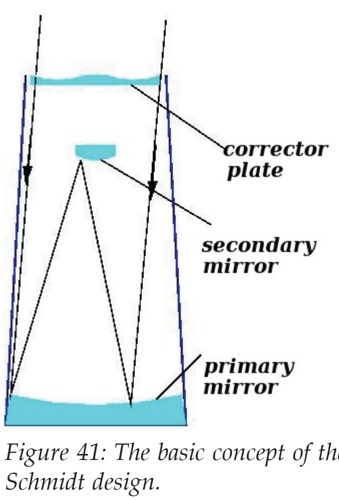


Figure 41: The basic concept of the Schmidt design.

survey of the northern sky, involving 1758 photographic plates. This Palomar Sky Survey became an important tool for the astronomers for decades to follow.

Observing the Sun

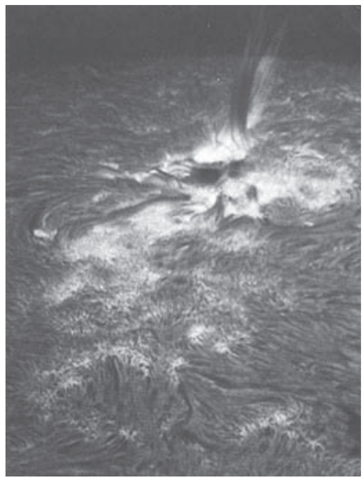


Figure 42: This spectro-heliogram shows the turbulent nature of solar atmosphere.

Another shortcoming of usual telescopes was the difficulty of observing the Sun through them. The main problem is the large amount of light from the Sun; one therefore needs a large instrument to spread the light to be able to analyse the details, but it is difficult to move large instruments to track the motion of the Sun across the sky. Jean Foucault was the first to suggest a 'heliostat' for a solar telescope. The heliostat mirror is flat; it rotates slowly driven by a clock and reflects sunlight into a fixed horizontal telescope. Lockyer used a heliostat for his 60-cm refractor, and later, in 1903, Hale built a 60-cm telescope at Mount Wilson. But the sunlight heated the air in the long telescope and distorted the image, and so Hale thought of a vertical, tower-like telescope.

Hale built a tower on Mount Wilson in 1912 with a large (45-m focus) telescope. Then he fitted a spectrograph to it, which allowed him to select the light from a narrow band of wavelengths, and studied the surface of the Sun in great detail. Janssen had found at the end of the 19th century that there were granules on the solar surface, and that they

Figure 43: The McMath-Pierce solar telescope was built in 1962.

moved constantly. Because of this motion, the light from the moving gas appeared at a slightly different wavelength, so photographing the Sun in *different* wavelengths showed gas moving *different* speeds. This 'spectroheliogram' showed that the solar atmosphere was turbulent, and also that sunspots were associated with magnetic fields. (Magnetic fields tend to split spectral lines, so studying the spectra from different parts of the Sun gives clues to the distribution of magnetic field there.)

World War II put a brake on scientific activity everywhere. Especially, research in topics such as astronomy that could not be used in the war effort was neglected. Some astronomers like Walter Baade at Mount Wilson, however, took advantage of the blackouts in cities that lessened the 'light pollution' and helped observations of faint objects. Baade managed to take exceptionally high resolution photographs of Andromeda galaxy, and discovered that there were two distinct populations of stars in spiral galaxies like Andromeda. One was an older population with less amount of heavy elements that inhabited a spherical region, and another, younger population (like our Sun) that inhabited the flat disc of the spiral galaxies.

The Hale telescope

Finally, the 5-m Hale telescope was installed in 1948 in Palomar. A new mounting system was used for it. There were two traditional systems of mounts: the fork (mostly for medium sized telescopes) and the yoke (for large telescopes). (Another, known as the German mount, using a counterweight for rigidity, was also used at times.) For the Palomar telescope, they modified the yoke mounting to allow it to swing over the Pole star. This arrangement is called a 'horseshoe mount' (Figure 44).

With the new telescope, Baade continued his study of the two populations of stars, and found a mistake in the distances measured by Hubble and corrected them. The universe according to his measurements was double the size estimated previously.

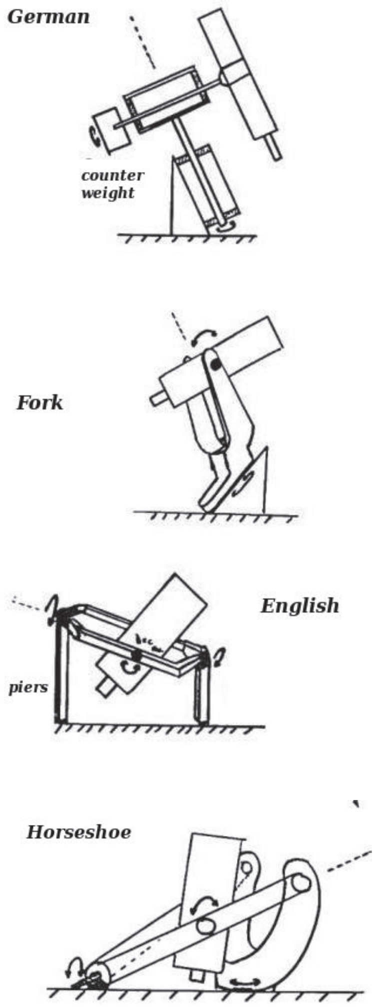


Figure 44: Different systems of telescope mounts are shown in the picture: the German, fork, and the yoke system that is also called the English mount. At the bottom is shown the horseshoe mount that was used for the 5-m Hale telescope.

8

Modern (and future) telescopes

Beyond photography

By the middle of the 20th century, astronomers began to use a new type of detector that greatly enhanced the research on faint objects. One problem with photographic plates was that there was no quantitative relation between the amount of blackening and the quantity of light that caused it. The new type of detector, called 'photomultipliers', used the idea that photons incident on metal surfaces can eject electrons (the photo-electric effect), which was explained by Albert Einstein in 1905. For thirty years after this discovery, scientists studied the response of various metals and coatings, to be able to make a device with which one could measure the amount of photons. The idea was to force the ejected electrons towards a positively charged plate (electrode) and produce a current that could be measured. The first such 'photo-cell' was used for astronomy by Paul Guthnick at Babelsberg in Germany in 1924, but the resulting current from starlight proved too feeble to register adequately. In 1930s, photo-cells began to be used to track bright stars and an automatic guiding system for telescopes was built.

Then it was realised that if the ejected electrons were made to impinge on other metal surfaces, they could chip off more electrons. And one could 'multiply' this effect by making the electrons hit more than one electrodes (Figure 45). This 'photo-multiplier' system was used by G. Weiss in 1936 and it produced a thousand times larger current than an ordinary photo-cell for the same amount of light. Vladimir Zworykin in USA then developed it further by 'guiding' the electrons through several stages, and achieved a million-fold gain over simple photo-cells. The advantage for astronomers was enormous. The first photo-multiplier tubes produced a pulse of a million electrons for a few photons, compared to just one blackened grain on a photographic plate for hundreds of photons.

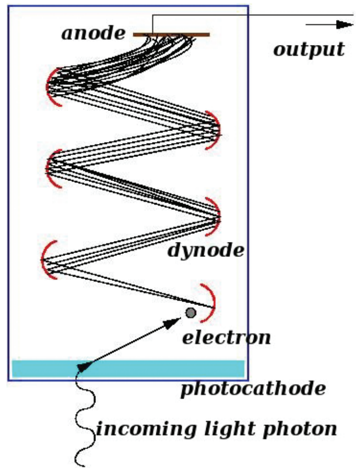


Figure 45: In a photomultiplier tube, the incident light photon strike a photocathode material and releases electrons. These electrons are then directed toward a series of electron multipliers, where electrons are multiplied by the process of secondary emission.

The use of photomultiplier tubes helped astronomers test the predictions of theories of stellar evolution and structure that was worked out before the war. Astronomers targeted globular clusters, which contained thousands to a million stars, and the detailed spectra of faint stars led to the confirmation of the theoretical ideas of stellar evolution. The use of photomultiplier tubes also made astronomers realise that even smaller telescopes with a good detector was useful, and for 20 years after the 5-m Palomar telescope, the telescopes that were mostly used were smaller than 5-m in size. Lighter materials were used for the telescope tube, allowing them to use the fork mount, as for example in the case of a 3-m telescope at Lick Observatory.

Still, the photographic plate had the advantage that it could record the images of all the stars in the field, whereas the photomultiplier could only produce a current that was proportional to the total amount of light incident on it. In 1936, A. Lallemand came up with a device to take a two-dimensional image with photo-electrodes, by focussing the ejected electrons on to a photographic plate. Another idea, by M. von Ardenne in 1936, was to make the electrons hit a phosphor screen, which was later photographed by a camera.


Figure 46: The 6-metre telescope in the Caucasus.

In the 1960s, scientists tried to digitise the process, first by using a silicon chip comprising of a micro-circuit with an array of diodes. Ejected electrons could be focussed on to the chip, which would then produce current from the diodes that are hit, and the magnitude of the current at different spots of the array could be analysed by a computer, giving a digitised image. Another process was to use a television camera with a light-sensitive material on which photons impinge, and analyse its electronic output signal. Astronomers using this 'Vidicon' system could see the image of stars on television screens, which greatly eased the process of observations compared to the earlier days when they had to guide the telescope and would not know until they had developed the photographic plates if they had properly exposed the plates.

New designs for telescopes

In the 1970s, a few telescopes were built in the 3.5 to 4-m size range. The Mayall telescope at Kit Peak, USA, then one at Cerro-Tololo in Chile and another at the Anglo-Australian Observatory in Australia, all used the Ritchey-Cretien design with a horseshoe mounting, but used mirrors of material that expanded little with heat, for example quartz or cervit. Then in 1976, a 6-m telescope was built on Mount Postukov in the Caucasus in modem day Russia. The telescope was designed to be driven by a computer, and used a alt-azimuth mount instead of equatorial mount. Traditional telescopes did not use this mount as both axes had to be driven in this case, and by different amounts. But since the Russian telescope was to be driven by a computer, this was not a problem, and as a matter of fact, the alt-azimuth mount was better for large loads.

Another new design was tried out in the case of the Multiple Mirror Telescope in Arizona, USA, which combined six 1.85-m telescopes in a single complex frame, and achieved an effective aperture of 6.5 metres. The individual mirrors were not kept aligned by any steel support system, but they were supported on a electrically driven system that constantly monitored the images and tilted and moved the mirrors until they were aligned. Another new aspect was a box-shaped building that acted as a dome, and which rotated with the telescope. It was much cheaper than the traditional hemispherical, spacious, domes, and was a pioneer in the making of future generation domes. In 2000, a 6.5-m mirror was cast for this telescope using a new technology that used a honeycomb structure inside an oven.

Then arrived a detector that has not only revolutionised astronomy, but also personal cameras. Charge-Coupled Devices (CCD) was developed in the 1960s and prototypes of an imaging system using CCD began to be built in the 70s. By 1990s, CCD cameras were being routinely used in large telescopes around the world.

Charge-Coupled Device (CCD) camera

A CCD imager is a two-dimensional array of light-sensing elements built on a silicon substrate. These light-sensitive elements are semiconductor junctions, which are essentially combinations of two materials with different energy levels for free electrons in them. When one side of this junction is put at a higher voltage (called 'bias voltage') than the other, the movement of electrons from one side of the junction to

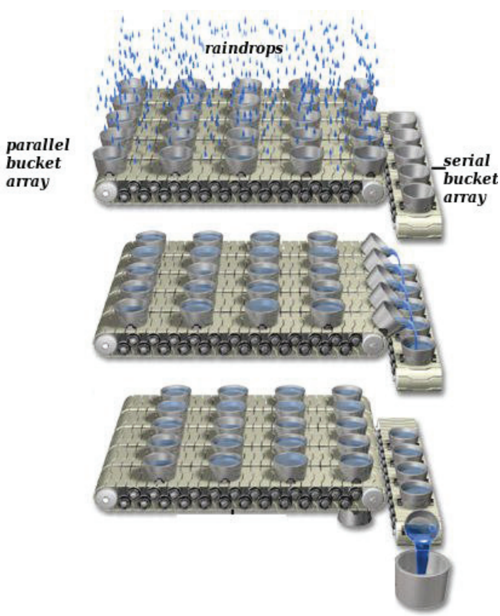


Figure 47: Consider an analogy of rain falling on an array buckets, in which the rain intensity varies from place to place (similar to photons incident on an imaging device). During an integration period, the buckets collect various amounts of signal (water). Then the buckets are transported on a conveyor belt toward a row of empty buckets. Finally, this row of buckets is shifted in a perpendicular direction. In this way, the contents of each bucket in the array is 'read out'. In the case of CCD, incident photons release electrons which are collected in each pixel (bucket), which are then 'read-out' in a sequential manner to produce an 'image'. Instead of conveyor belt moving the buckets, the pixels in CCD are coupled to each other by their transporting charges, which is why it is called a Charge-Coupled Device.

the other can be controlled. These light-sensitive elements in a CCD are so arranged (with a bias voltage) that they trap any electrons ejected by incoming photons.

Each 'picture element'— or *pixel*— collects these electrons, and then these charges are shifted onto an adjacent pixel, like a row of people passing on buckets of collected water, and the amount of charge in each pixel is recorded, and then the image is reproduced. Once the 'read-out' is over, the CCD imager is ready to take another image, i.e. collect electrons and then pass on the packets of charges serially. It is called a charge-coupled device because the elements are coupled to one another by transporting charges (Figure 47).

By mid-1970s, engineers had built a CCD imager with 100 × 100 pixels (meaning 100 rows and 100 columns), but the charge transfer efficiency was not good enough for astronomical purposes. But soon, in 1979, a cooled, 312 × 520 pixel array CCD camera was installed on a 1-m telescope at Kitt Peak, and it immediately won over the astronomers. The efficiency of converting photons to electrons was almost perfect, and the amount of charge was proportional to the number of photons. In the case of photographic plates, this proportionality is not always obeyed, and so it is difficult to estimate the amount of light from the amount of blackening of plates. Moreover, one could use different materials for a CCD for recording light of different wavelengths, and so a modified CCD could be used to take image in ultraviolet or infrared rays. In addition, the contrast between faint and bright sources in a CCD image was much better than in a photograph.

There is some 'noise' in the detector though. Some pixels collect spurious charges in the absence of light, because of the inherent nature of the material used, and sometimes because of the temperature it is used at, or degradation of the material over time. Sometimes stray energetic particles entering the atmosphere leave their marks on CCD images. But these are minor disadvantages compared to the enormous gain in the case of astronomical imaging. It is therefore not surprising that CCD imaging system has now become the mainstay of modern astronomy.

As it has happened previously, technological innovations always helped small telescopes do forefront scientific research, even when astronomers strove to build big telescopes. At the end of the 20th century, CCD imaging helped doing exciting science with small telescopes. It led to path breaking results even with 1-2 metre sized telescopes that could spend dedicated time on some projects, which big telescopes with huge demand on their time could not afford to. In the mid 1980s, astronomers began to map the universe, plotting the positions of galaxies according to their distances, which was an extension of Herschel's old project of mapping the stars in our Galaxy, now carried to the case of galaxies in the universe.

The first results showed that the galaxies were not uniformly distributed in the universe: there were structures, and there was also a hierarchy of structures. Galaxies were gathered into groups, which together formed big clusters of galaxies, and then there were superclusters of galaxies. This gave a spurt to theoretical studies of how structures could evolve in the universe, whose predictions were tested against better maps of the universe that were available in the 1990s. A survey began in 1991 using a 1-m telescope at Las Campanas, Chile, was a pioneer. Then, a survey with the 3.9-m *Anglo-Australian Telescope* in Australia (completed in 2003) determined the distances of 200,000 nearby galaxies. They used fibre-optics technology to lead the light from different galaxies in a single field to get their spectra, instead of taking the spectrum of each galaxy one by one, a process which would have taken many more years. Finally, the *Sloan Digital Sky Survey*, done with a 2.5-m telescope at Apache Point, USA, determined the distances to almost a million galaxies between 2000 and 2008, and made a detailed map of the nearby universe, apart from making other important discoveries along the way.

Removing the effects of the atmosphere

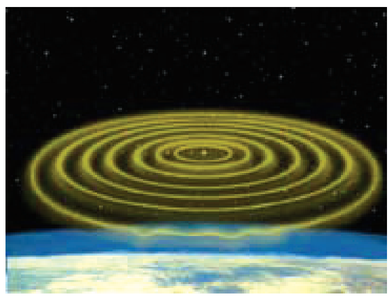


Figure 48: The wavefront of light coming from a star is distorted by our atmosphere which blurs its image recorded in a telescope.

Another development in the telescope design has taken the building of modern telescopes leagues ahead of their counterparts from the 20th century. It attempts to remedy a problem that has plagued astronomers for ages: the twinkling of stars. Stars twinkle because the light waves are corrupted by disturbances in the Earth's atmosphere, arising from different temperature layers, or from different wind speed. A pebble thrown into a still pond creates waves that expand uniformly. Similarly, waves of light from a star propagate through empty space in a regular fashion. The 'wavefront' remains spherical unless it is disturbed by hitting something on its way. Upon entering the atmosphere though, the wavefront is disturbed and gets corrugated (Figure 48). A wrinkled wavefront implies that the eye would register the wave coming from slightly different directions (perpendicular to the wavefront entering the eye at that moment) at different times, which is the reason behind twinkling of stars.


Figure 49: The Hubble Space Telescope was launched in 1990.

Astronomers in the 20th century began to build telescopes on mountains where the effect of the lower, turbulent atmosphere is small. A century later, their attempt to avoid the effect of the atmosphere led to two solutions. One was the expensive way of sending a telescope in space and avoiding the atmosphere altogether: it led to the development and launching of *Hubble Space Telescope* in 1990. The other was the development of adaptive optics, by which either the mirror is manipulated in a way so as to cancel the atmospheric effect, or one monitors the atmospheric effect by some means and subtracts it from the disturbed images of stars.

Astronomers in the USA proposed a space telescope in the 1970s, but problems with space shuttles in the 1980s set back its schedule. When it was launched in 1990, *Hubble Space Telescope* had a 2.4-m mirror, a high resolution spectrograph (that could detect a spectral line as narrow as 1/90,000th of the wavelength of light), and a wide field camera among other instruments. After the launch, the mirror was however found to be flawed. It suffered from spherical aberration so that light rays reflected from different parts of the mirror were not brought into a single focus. This mistake was corrected by adding two extra mirrors in the light path during a servicing mission to the telescope in 1993. Three more servicing missions have visited the telescope: once in 1997 (to install a near-infrared camera), and twice in 1999 (to replace gyroscopes aboard the telescope, to help its pointing, and to install a new cooling system). Another mission is now being planned to make the *HST* working until 2015.

Hubble Space Telescope

The absence of atmospheric effect for the space telescope and the surface accuracy of the mirror (correct to about 10 nanometres) implied that it would be able to observe celestial objects in great detail. It does not mean that the telescope would see details at any *arbitrary* level: the wave nature of light limits the performance of any optical instrument.

Light waves reflected from different parts of the mirror in a telescope combine to form rings around the image of a star, and the sizes of these rings depend on the wavelength of light. These are called diffraction rings. If one observes two stars close to one another in the sky, then the rings from one star would overlap with those of the other star (Figure 50). The amount of overlap would depend on the ability of the telescope to separate the central bright spot (which depends on the diameter, D, of the mirror), and the size of

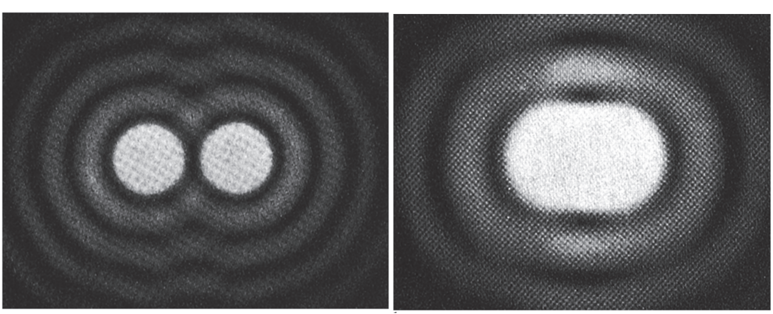


Figure 50: The diffraction pattern of two point sources of light, as seen through a telescope, limits the ability of telescopes to 'resolve' two adjacent sources. In the left, two sources are barely resolved, and on the right, the two sources appear as one blurry object.

the rings (which depends on the wavelength, λ, of light). Effectively, the ability of a telescope to 'resolve' two adjacent point sources of light in the sky depends on the ratio between these two parameters, and the smallest angle achievable (in the absence of atmospheric effects) is roughly λ/D. For the Hubble Space Telescope, this is about 1/20th of an arc second, an unprecedented resolving power in the history of astronomy. Earth bound telescopes that suffer from atmospheric disturbances, even from the best sites, cannot go below half an arc second or so, and the space telescope offered a ten-fold increase in the resolving power.

HST has helped astronomers in learning more about almost all types of astronomical objects than was previously known, from detailed images in optical to ultraviolet, to spectroscopic studies. In 1996, the telescope took a long exposure photograph of a small part of the sky for ten days and recorded the images of galaxies so distant that the universe was a tenth of its age today when the light we see today left the galaxies. Another long-exposure (more than 11 days) photograph taken in 2003 managed to detect galaxies from about 13 billion years ago (the age of the universe being about 13.7 billion years) (Figure 51). Our knowledge of the universe changed forever after the launch of *HST*.

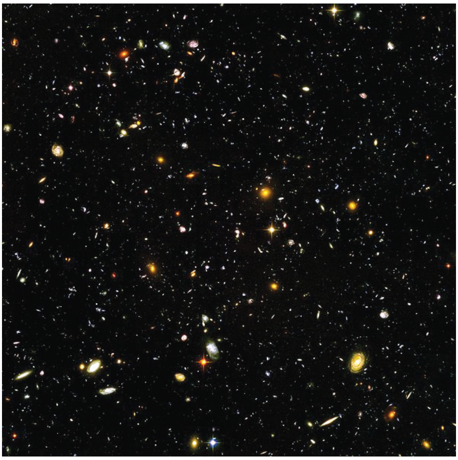


Figure 51: The Ultra Deep Field, a long exposure picture taken by the space telescope that revealed galaxies, formed barely half a billion years after the big bang.

Active and adaptive optics

It is expensive to launch and maintain a space telescope, and one needs some other approach for ground based telescope to remove the effects of atmosphere. Telescopes built at the end of the 20th century and later were designed to use 'adaptive optics' or 'active optics'. In adaptive optics, the wrinkles on the wavefront of light coming from a 'guide star' are analysed by a computer, which then calculates the way a mirror should be deformed so that the wrinkles are compensated and the wavefront becomes spherical again. The mirror is made up of segments which can be tilted on two axes. After the analysis by the computer, which takes about a micro-second, the mirror is deformed by tipping and tilting the segments, and a better image is produced. The first requirement is to analyse the wavefront of a guide star, and for that normally a laser is used to produce a reference light source in the atmosphere. The laser light

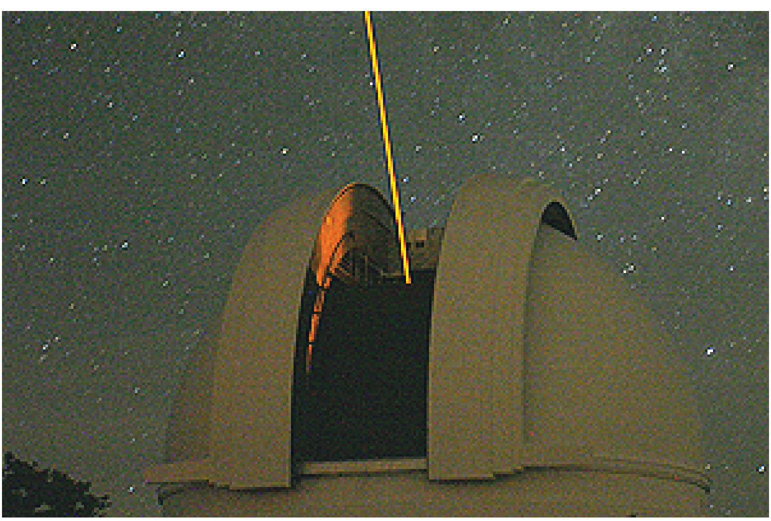


Figure 52: In adaptive optics, the image of a laser guide star is analysed to determine the distortion caused by the atmosphere, and how to compensate it.

excites sodium atoms in the upper atmosphere to 'glow' like a star, whose image is analysed to characterise the distortion caused by the intervening atmosphere.

In active optics, the primary mirror is mounted on 'actuators' which are essentially a sort of motor-driven springs, so that the mirror shape can be changed by applying suitable force underneath it. Thin primary mirrors are used in this case, which help to keep it lightweight and flexible. The wavefront of the reflected rays is analysed by a detector at the focus, by keeping track of the image of a star outside

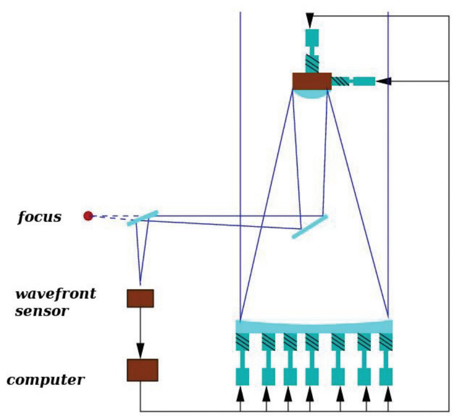


Figure 53: In telescopes with active optics, the primary mirror is deformed by 'actuators' to compensate for the distortions caused by the atmosphere, as analysed by detectors near the focus.

the main target, so as not to disturb the observation process. The image of this star is analysed and compensations required to make the wavefront wrinkle-free are calculated, and communicated to the actuators below the primary mirror (Figure 53).

A number of large telescopes were built in the 1990s and years following it based on these ideas, and they managed to achieve an angular resolution of about half an arc second. A 10-m aperture telescope, called the *W. M. Keck Telescope*, was built on the Mauna Kea Mountains (at about 4,666-m) in Hawaii that started observing in 1993. Another similar sized telescope was added to the system, situated at 85 metres away from the first telescope. A 8-m telescope was built nearby, called the *Subaru* telescope, in 1999. Then another two 8-m sized telescopes were built in Hawaii and

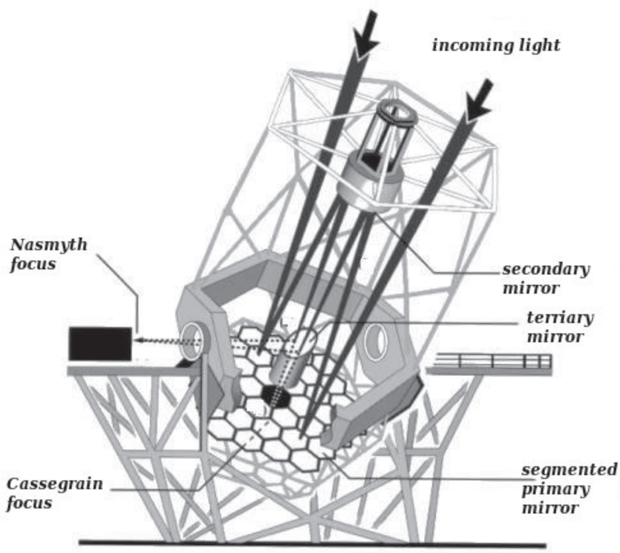


Figure 54: The primary mirror of the Keck Telescope consists of many segments..

Chile, called the *Gemini* telescopes, in 2000. And a cluster of four 8.2-m-sized telescopes were set up (the *Very Large Telescope*) in Chile. The cost of building and operating these large telescopes is extremely high, and in most cases, many organizations from different countries have come together to build and maintain these telescopes. At the time of writing, the largest telescope on ground is the 10.4-m telescope in the Canary Islands.

Figure 55: Proposed design for the Giant Magellan Telescope.

There are now plans to build one or two very large telescopes, in the range of 25-30 metres in aperture. The proposed *Thirty Meter Telescope (TMT)* will consist of more than four hundred segments for the primary mirror, each mounted on actuators, and there will be a secondary and a tertiary mirror to help focus the light rays. The *Giant Magellan Telescope (GMT)* will have six 8.6-m mirror segments, which will be equivalent to a 24.5-m size primary, and the secondary will consist of seven segments. Design studies of both proposals are currently underway, and they are likely to be operational by around 2015.

9

Radio telescopes : I

When astronomers began to build metre-sized telescope on mountains at the beginning of 20th century, physicists and electrical engineers were busy with another development that would open up a whole new window to astronomy. These experiments had to do with producing and detecting radio waves, which were electromagnetic waves like light, but with a longer wavelength. While the waves of visible light had a wavelength of about 500 nanometres, radio waves had a wavelength larger than a millimetre or so.

Detecting radio waves

James Clark Maxwell theoretically explained in 1865 that electric and magnetic fields could act on one another to produce a train of waves: a change in the electric field at one place generated magnetic fields around it, and this change in the magnetic field in turn created an electric field. Once the electric field is disturbed at one place, an electro-magnetic train of waves would be generated, whose wavelength would depend on the frequency of the original disturbance. And it travelled through space with the speed of light that physicists had determined in the 19th century, of about 300,000 kilometres per second. In 1880s, Heinrich Hertz demonstrated how to create radio waves of centimetre wavelength, while in India, Jagdish Chandra Bose experimented with millimetre wavelength radiation (microwaves).

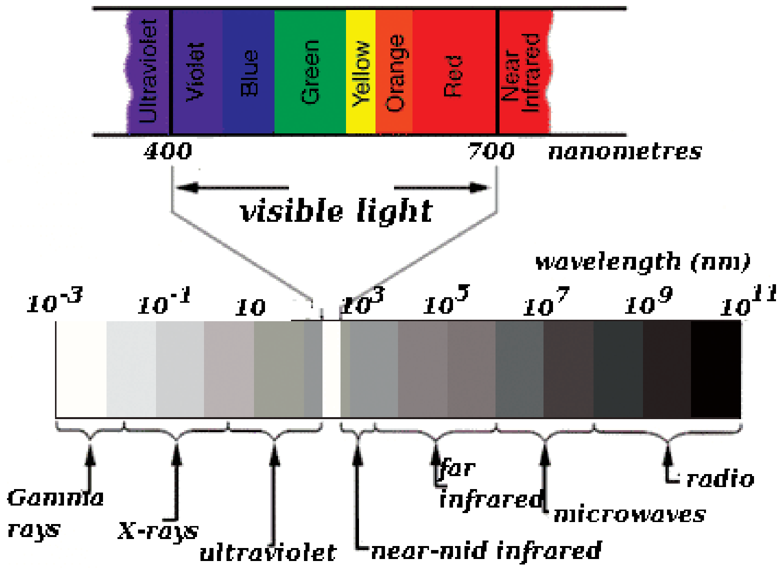


Figure 56: The spectrum of elecromagnetic waves, of which the visible light forms a part.

Broadcasting radio waves began after the First World War, and the wavelengths in use gradually shifted to the shorter side over time. Soon, radio engineers realised that the performance of their radio receivers was limited by a 'static' noise, and because of the commercial importance of radio stations, they decided to investigate it in detail. Karl Jansky built a receiver for 15-m wavelength radiation that was used at that time for ship-to-shore communication. He built an antenna with an array of aerials, mounted on a 30-m long and 4-m tall frame, which was set on wheels so that it could be rotated to study the effect of the 'noise' from different directions of the sky. In 1933, Jansky found that apart from the noise from thunderstorms, there was a steady hiss, as though produced by a bad amplifier. When he studied this hiss with regard to different directions of the sky, he realised that it came from a portion of the sky that *moved with the stars*. As a matter of fact, he had detected radio waves coming from the centre of Milky Way.

This discovery was set aside by Bell Telephone Laboratories for which Jansky did his study, because it did not fit into their commercial aims to study radio waves from celestial objects. In 1937, Grote Reber decided to study this 'cosmic static' with short wavelength (9-cm) waves, and built a 9.4 metre telescope, made of wood with a surface of galvanized iron for the 'mirror'. Radio waves behave exactly like light because they are both electromagnetic waves, and rays can be brought into a focus by using a reflecting surface. At the focus, there would be a wire aerial to collect the waves and to convert it to electrical voltage that can be amplified and recorded. Since radio waves are much longer than visible light, the accuracy of the reflecting surface need not be as perfect as optical mirrors. One needs to have a surface that is accurate to about a tenth of the wavelength, and so for 9-cm long waves, an accuracy of a centimetre was enough.

Figure 57: Karl Jansky with his telescope near Holmdel near New York, USA.

After a few unsuccessful attempts, Reber finally detected radio waves at 1.9-m wavelength from the Milky Way. His telescope was not steerable though, and could observe the portion of the sky along the north-south line (the meridian, like Römer's transit telescope in the 17th century). Pointing his telescope at different elevations (along the meridian) every day, Reber made a map of the intensity of radio signal over the sky. Since he used rather long waves, his angular resolution (arising from the diffraction pattern, as we found in the case of optical telescopes) was poor: the diffraction rings for radio are wider and tend to blur the 'image' of sources. The diameter of Reber's telescope was about five times the wavelength, and therefore he could not see details smaller than about 1/5th of a radian, or about 12 degrees across.

During World War II, sensitive instruments were built to detect short wavelength signals, and engineers focussed on the development of radar technology. While studying a unwanted source of noise that affected the British anti-aircraft radar sets, James Hey found that the source of the noise was the Sun. Then in 1942, radio signals at short waves (microwaves, of wavelength 3.2-cm) were detected using a sensitive receiver, and it was confirmed by Reber in 1944. The intensity of the signal was as expected from a hot, opaque body at about 6,000 Celsius, which was known from the study of its spectral lines.

One problem that beset the early radio astronomers was the difficulty of taking data for a long time (equivalent to taking long exposure photographs in optical), since the response of the system changed over time. After the war, Robert Dicke in USA devised a method in which the telescope would switch between the target and a standard, calibration source, so that even when the system response changed over time, it would affect the target and the standard source equally, and so one could take the difference between two, which would be a record of the real intensity, independent of the changes in the response system. With this method, Dicke was able to measure signals that were about one-ten thousandth of the noise level, which basically came from abrupt changes in the response system.

Radio interferometers

But even when one could take data for a long time, the angular resolution was so poor that for the Sun, for example, it was not possible to resolve the sources of radio emission on the solar surface. After the war, physicists and engineers began to experiment with interferometers to increase the resolution power of radio telescopes.

Consider a point source in the sky, and two radio telescopes that receive signals from it. By a 'point' source, one means that its detail structure is 'unresolved' as observed by the telescope. The radio waves would hit the telescopes in phase and out of phase alternately, as the Earth rotates and causes a change in the difference in path from the radio source to the two telescopes. This is like the band of dark and bright 'fringes' one observes for light coming out of two slits (as Young had demonstrated in 1801). In the case of light, the fringe pattern carries

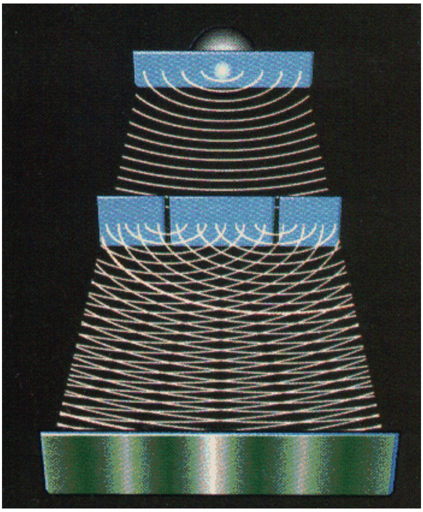


Figure 58: Interference between light emerging from two slits cause a band of dark and bright 'fringes' to appear at a distance.

the information of the distribution of light across the source. If one changed the distance between the slits, and records the fringe pattern for different slit distances, one could recover the brightness variation across the source, or in other words, 'image' the source. In radio, one can use pairs of telescopes as the 'slits' and from the records of fringes for different pairs, one could find the radio image of the source. Effectively, the finest details in the image would be provided by the *widest* pair of telescopes, which would be a measure of the *effective size* of the combined telescope system, called the 'interferometer'.

The first success in interferometry came from a brilliant idea, of using sea as one 'mirror'. J. L. Pawsey in Australia set up an antenna on a cliff looking out to the sea and observed the rising Sun. The surface of the sea acted like a mirror for the 1.5-metre wavelength radio waves, and the instrument worked as though there were *two* telescopes (or two slits): one on the cliff top and another, the sea surface (Figure 59). In 1946, astronomers were able to locate the source of intense radio emission from the Sun at a big sunspot. At about the same time, a team at Cambridge, UK, under Martin Ryle used two aerials and also detected the sunspot in radio emission.

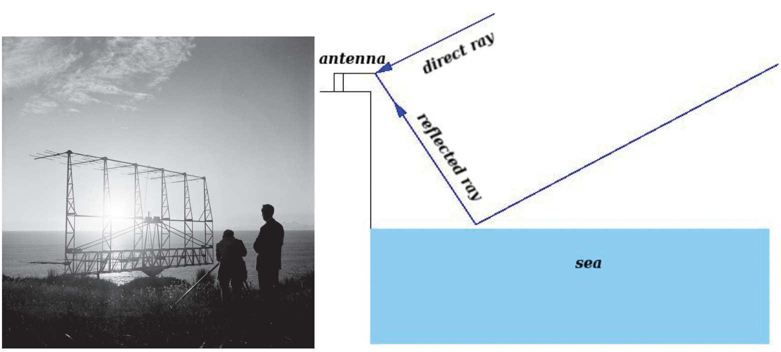


Figure 59: Cliff-top interferometer in Australia combined the direct ray and the reflected ray from sea to determine the position of radio sources to good accuracy.

Then the Australian cliff-top interferometer was used by J. E. Bolton and G. J. Stanley to observe a new, puzzling source of radio emission in the Cygnus constellation that was discovered at that time. They showed with their interferometer that the source of emission was less than 8 arc minutes across. It could not be identified with any known visible object in the sky though, since there were many light sources within a circle of 8 arc minutes in diameter in the sky. Astronomers across the world began to scan the sky for other such radio sources in the sky other than the Sun. In 1949, Bolton's group found a few more radio sources that could be identified with known objects, including M1 (the first object in Messier's catalogue, also known as the Crab nebula, which we now know as the debris of a supernova in our Galaxy), and M87, which was a distant galaxy.

Hanbury Brown used a 66-m diameter telescope at Jodrell Bank, UK, and another small mobile telescope (of 6-m in size) to do interferometry, by connecting the two telescopes with a radio link. The first trial in 1954 put the telescopes at a separation of 910 metres, then the distance was increased in steps to increase the angular resolution. By 1956, they could use a separation of 20 kilometres, which amounted to about 11,000 times the length of radio waves used. This implied that the angular resolution— which depend on the ratio of wavelength to the diameter (in this case of interferometry, the distance between the pair of telescopes)— was about 12 arc seconds.

In Australia, a cross-shaped array of many aerials was built by B. Y. Mills in 1952, its arms being 450 metres long. It could not track the sources though, and was used to observe objects overhead during their transit. W. N. Christiansen then replaced the aerials by small, individual radio telescopes, and was able to image the Sun during the epochs of low and high sunspot activity. The gaseous periphery of the Sun— the corona that becomes visible during total solar

Figure 60: The 76-m telescope at Jodrell Bank.

eclipses— emits a large amount of radio waves, and so the radio 'image' of the Sun appears bigger than the optical Sun.

Details of images cannot however be studied if the signal is not large. For large signals, one must collect a large amount of radio waves, and so one needs large telescopes. Also, it was easier to track objects in the sky with a single telescope. At the time of the first interferometer studies at Jodrell Bank, a large (76-m in diameter), steerable radio telescope was also built there in 1957. The telescope was put on a circular railway system to be able to rotate it, and it could be steered along another axis. Another 25-m telescope was built in 1956 at Dwingeloo, Netherlands, mainly to study the emission from interstellar hydrogen atoms. In 1957, a pair of telescopes, each of 27-metre size, was built at Owen's Valley, California, USA. One of the pair was mounted on a 1 kilometre-long railway track, so that observations could be made with many 'pairs' by putting the mobile telescope at different distances from the fixed one.

The Dutch effort to study emission from interstellar hydrogen became an important topic of study for radio astronomers. During the war in 1944, two Dutch astronomers, Jan Oort and Hendrik van de Hulst predicted that hydrogen atoms should emit photons of radio wavelengths (21-cm long) due to an internal realignment of the proton and electron inside the atom. This line emission was 'forbidden' in high-density regions (like the forbidden optical lines we encountered earlier), because collisions between atoms de-excited the atoms often and did now allow them to de-excite by emitting this radiation. In the tenuous gas of the interstellar space, however, this radiation would be a dominant emission feature. Oort and van de Hulst predicted that this 21-centimetre emission from the vast amount of hydrogen atoms in our Galaxy should be large enough to detect. This emission was detected in 1950 by a few astronomers, including a team led by Oort in the Netherlands. Ryle's team also detected similar emission from hydrogen atoms in the Andromeda galaxy at this time.

The observation of 21-centimeter radiation became a mainstay of radio astronomers in the following years, and in many ways, it gave a better idea of the structure our Galaxy and others than was possible with optical telescopes. Visible light from distant stars is attenuated by scattering from gas and dust in the intervening space, and dust grains in space mostly affect waves that are smaller than their size. Dust grains in space are micron or smaller in size, and so it is the visible (and shorter wavelength waves, like ultraviolet) light that suffers most from dust scattering. As a matter of fact, the dust in our Galaxy acts like an opaque screen for stars beyond a few thousand parsecs from the Sun— all visible stars are quite nearby. Therefore, it is difficult to get an idea of the overall structure of our Galaxy by examining the visible light coming to the Earth. The studies using visible light in 1950s had given hints of a spiral structure in our

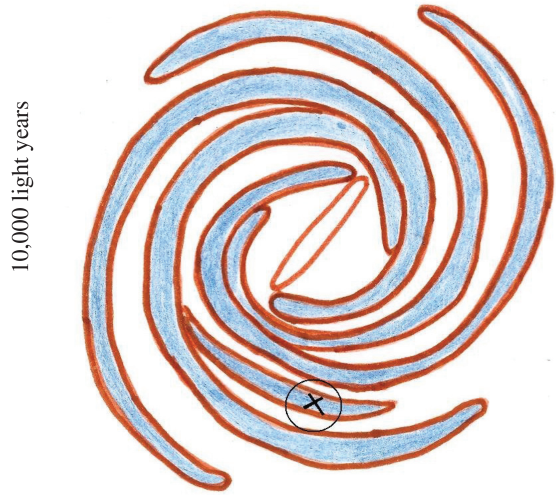


Figure 61: Milky Way as it would appear from above its flat disk. The spiral structure is delineated by hot, blue stars. Cool, orange and red stars are found in and between the spiral arms. The Sun's location in the Galaxy is marked with 'X': we are not at the centre of Milky Way. Interstellar dust limits our view in optical light to roughly the area within the circle shown around the Sun.

Galaxy, but it was not known if our Galaxy was a spiral galaxy like the Andromeda or other spiral galaxies.

Radio waves are a different matter altogether. Their long wavelength allows them to skirt around the grains of dust and reach the Earth almost unimpeded. And since hydrogen atom is the most abundant element in the universe, the observation of 21-cm emission became an important tool for astronomers soon after its discovery. Observations by Dutch and Australian astronomers in late 1950s revealed the spiral arms whose optical emission was blocked by intervening dust, but whose radio emission reached the Earth (Figure 61). Our Milky Way was indeed found to be a spiral galaxy like many others teeming in the universe. Herschel's dream of being able to map the Milky Way in 1780s had come true almost two centuries later.

10

Radio telescopes : II

Studies with the first radio interferometer with steer-able dishes at Owen's Valley, USA, led to an exciting discovery. Astronomers could now pinpoint the positions of radio sources to within a few arc seconds, which could allow optical astronomers to scan selectively a certain portion of the sky, to find if the radio source could be identified with any visibly bright object. Cambridge astronomers had produced a catalogue of bright radio sources, and T. H. Williams used the Owen's Valley telescopes to study a source that was 48th in that list, and therefore called 3C 48 (the 3C standing for the 'third Cambridge catalogue'). Alan Sandage then used the 5-m telescope at Palomar and found a star at the position of 3C 48, that was unusually blue. Then Cyril Hazard at Jodrell Bank developed a method of getting accurate positions of radio sources that crossed the path of the Moon, by noting the exact moment when the radio source was eclipsed by the Moon, since the position of the Moon was known extremely well. These positions were then checked by astronomers using the 5-m telescope.

Quasars

Soon, a few more radio sources were found to coincide with very blue 'stars', and their optical spectra showed bright emission lines instead of the usual dark absorption lines from other galaxies. Also the emission lines appeared at unexpected wavelengths. Then Maarten Schmidt discovered that they appeared at odd wavelengths because they had been shifted by a large amount. The shift in wavelength implies a tremendous speed for the object 3C 48, about 50,000 kilometres per second. This 'star' could not then belong to our Galaxy, and it most likely belonged to a galaxy that was receding away from us because of the expansion of the universe, as Hubble had showed. But this interpretation led to a puzzle. If the object was so distant, then its actual brightness must be very bright, many times brighter than our own Galaxy. But a study of the fluctuation in its brightness showed that the source must be about a light year across. How could such a small object emit so much light?

These objects were called Quasi-stellar objects, or quasars, because they had the images of a star, not fuzzy like galaxies. Yet, they had the brightness of hundreds of galaxies put together, and all of the energy emanated from a tiny region of space like our solar system. Astronomers had discovered these strange objects by using electromagnetic waves in *more than one* wavelengths— in optical and in radio. This discovery demonstrated the power of using data from many wavelengths for the first time, and it set a trend for modern astronomy. Multi-wavelength astronomy is an essntial tool of astronomers these days. Waves of different wavelengths give clues to different aspects of an object, and act like pieces of a jigsaw puzzle, each helping the scientists form an idea of the nature of the object.

At this point of time, Martin Ryle began to do the equivalent of Herschel's project of mapping the universe, but with bright radio sources, using an interferometer at Cambridge, UK, consisting of three (18-m) telescopes, two of them fixed to the ground, and the third being mobile. The largest distance between the pairs was half a mile (0.8 kilometres). Ryle pioneered a technique of synthesizing the data, taken during long periods using the interferometer, and producing an image as though it was obtained by a complete half-a-mile radius telescope, called 'aperture synthesis' (for which he was awarded the Nobel Prize in 1983).

Microwave background radiation

Like Herschel, Ryle assumed that all bright radio sources were of comparable brightness, and therefore their apparent brightness was an indicator of the distance. In this way, he attempted to map the distribution of the bright radio sources in the universe, and found that they were not uniformly distributed. There were too many faint galaxies than expected from a uniform distribution, and he interpreted it as the sign of *evolution* of galaxies over time.

At that time there was a debate raging among theorists. Hubble had shown that the universe was expanding. But has it also been *evolving?* One camp held that it did, and began as a hot, dense and mostly uniform universe which then cooled down and formed galaxies. The other camp advocated an eternally unchanging (but expanding) universe. Ryle's data appeared to favour the evolving model.

In 1965, a remarkable discovery was serendipitously made by two radio astronomers that settled the issue in favour of the evolving ('big bang model') model. Arno Penzias and Robert Wilson at Bell Telephone Laboratories were studying a background 'noise' for an antenna system operating at 7.35-cm wavelengths (microwaves) for use in communication through artificial satellite. The exercise was reminiscent of Jansky's experiment in 1930s. After eliminating all possible sources (which involved cleaning

Figure 62: Arecibo telescope in Puerto Rico.

their horn antenna[1] of pigeon dropping), Penzias and Wilson found that a signal came from all directions in the sky.

By coincidence, Robert Dicke was trying to detect a signal at that time in microwaves which was predicted by theorists to be a relic of the radiation from early, hot and dense universe. As the universe cooled down, the highly energetic (short wavelength) radiation in the primitive universe would have cooled down to acquire long wavelengths like microwaves, equivalent to radiation from a cold body at about -270 degrees Celsius, or 3 degrees Kelvin. Dicke's result along with Penzias and Wilson's data proved to the astronomers beyond doubt that the universe did have an early and hot phase, and that it was liable to evolve.

1 Incidentally, the concept of a horn antenna was originally pioneered by Jagdish Chandra Bose for his studies with microwaves in 1895.

The discovery of this 'cosmic microwave background radiation' was probably the most significant astronomical study about the history of the universe after Hubble's discovery of the expansion of the universe, and again, it demonstrated the usefulness of data gathered in different wavelengths.

Solar system studies

Radio astronomers did not study only distant sources— their study of the solar system objects also opened up new vistas. Venus was difficult to study in visible light because of its dense cloud cover. In the 1960s, several telescopes—including the 305-metre (1,000-foot) radio telescope at Arecibo, Puerto Rico, for which the dish was fit into a bowl-shaped valley—were used as radars to study the rotation of the surface of Venus. It was found that the planet rotated around an axis perpendicular to its orbit, and rotated backward compared to all other planets in the solar system. Astronomers found interesting results from radar studies of Mercury as well. Earlier, it was thought that Mercury rotated around its axis at the same rate as it revolved around the Sun, but new radio measurements showed that the length of its 'day' was two thirds of its 'year'. Studies of the surface of Mars showed it to have mountains taller than any on Earth.

The radar measurements were so accurate that the distances of planets came to be determined to within an accuracy of one part in a hundred billion. This sort of accuracy helped radio astronomers to try testing the tiny modifications required from the predictions of Einstein's theory of gravity: radar reflections from Mercury was found to be delayed by one hundredth of a microsecond while passing close to the Sun, as required by Einstein's theory.

Pulsars

The support for Einstein’s theory encouraged the theorists to study the effects of other predictions, such as black holes which are objects so massive that light cannot escape their gravity. Towards the late 1960s, astronomers began to suspect that black holes could be culprits behind quasar’s production of energy from a tiny region. When matter near a black hole falls on it, an enormous amount of energy could be released in various wavelengths. One way to study the central part of quasars was through the twinkling of its light (radio waves) as it passed through disturbances inside the solar system. Just as atmospheric disturbances on Earth produces twinkling of stars, inter-planetary disturbances arising from matter thrown out of the Sun can create ‘scintillation’ of radio signals from quasars.

Antony Hewish built a large array to study this scintillation. One needed a large collector to be able to gather enough signals quickly, because one could not take ‘long exposure’ data for scintillation. This telescope made a serendipitous discovery in 1967. It found objects that emitted pulses of radio signals with an extreme regularity, like a good clock. The first such ‘pulsar’ sent out signals every 1.33 seconds, and the first interpretation was that it was from an extra-terrestrial intelligent community. But this idea was discarded when several such pulsars were discovered soon thereafter. In 1968, a pulsar was identified with a visible star, and Arecibo telescope found a pulsar in the Crab nebula, which was known as the debris from a supernova that went off in 1054 AD. In 1969, a star was discovered in this nebula that flashed in sync with the radio pulses.

Gradually, theorists understood that pulsars were remnants of supernova explosions, which occur to massive stars at the end of their fuel supply for thermo-nuclear

Figure 63: The Very Large Array in New Mexico, USA.

reactions that produces light. A dense and compact remnant core forms at the core, and the outer layers of a massive star are ripped off during a supernova explosion. This compact star is made of mostly neutrons, a particle like the proton, but without any electrical charge.

The study of pulsars and quasars brought the study of Einstein's theory into sharp focus. Extremely massive stars were expected to leave black holes as remnants, which would probably trigger a quasar-like phenomena, whereas intermediate mass stars would leave pulsars/neutron stars as remnants.

Large interferometers

The study of these objects, and others, was aided by the setting up of a new, large interferometer at the desert of New Mexico, USA in the middle of 1970s. The *Very Large Array*

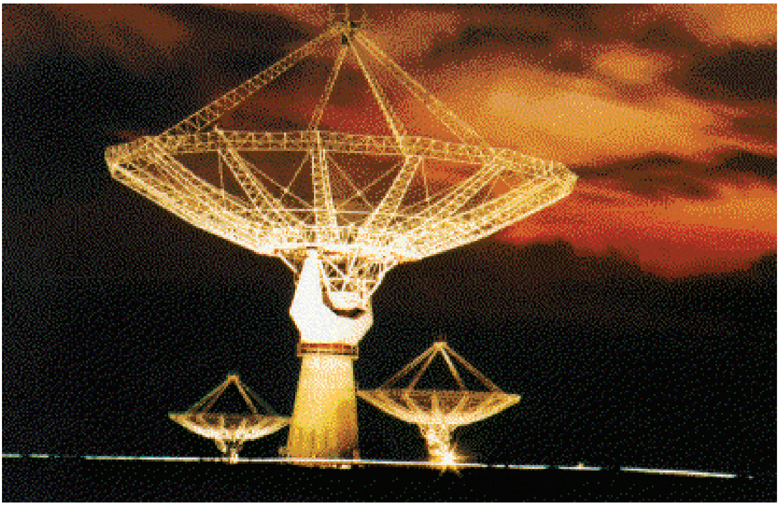


Figure 64: GMRT near Pune.

consisted of 27 radio telescopes, each 25 metres in aperture, and the array was laid out as a Y-shape with arms 21 kilometres long. Each arm was a railway, and the telescopes could be moved to make the optimum aperture that the observations needed. A large telescope operating mostly in long wavelengths (above 20-cm) was built in India, near Pune, in mid-1990s under the leadership of Govind Swarup. This *Giant Metre-wave Radio Telescope (GMRT)* has thirty telescopes, each 45-m in size and spread over an area, the largest separation between the telescopes being 26 kilometres.

In the early 1990s, astronomers even tried to synthesise signals from telescopes separated by thousands of kilometres. These *Very Long Baseline Arrays* were set up in Europe and in the USA and they achieved an angular resolution of about a millionth of an arc second (micro arc second). Towards the end of 20th century, a few telescopes were launched aboard satellites, the data from which could be synthesised with Earth-bound telescopes to achieve even finer angular resolutions. Suddenly, radio telescopes not only seemed to have caught up with the resolution of optical telescopes— beginning with producing blurry radio images before 1950s, and reaching a micro-arc second level accuracy by the end of the century— but also left them leagues behind.

With these telescope, astronomers began to study the details of processes by which black holes in quasars threw matter out in space. Individual knots of dense gas were tracked as they were ejected by energetic processes near the black holes and ploughed through the material of the host galaxy out to the intergalactic space. Since the quasars are very bright, they could be observed even from large distances, and soon the study of quasars became a tool to study the evolution of the galaxies, and that of the universe as whole.

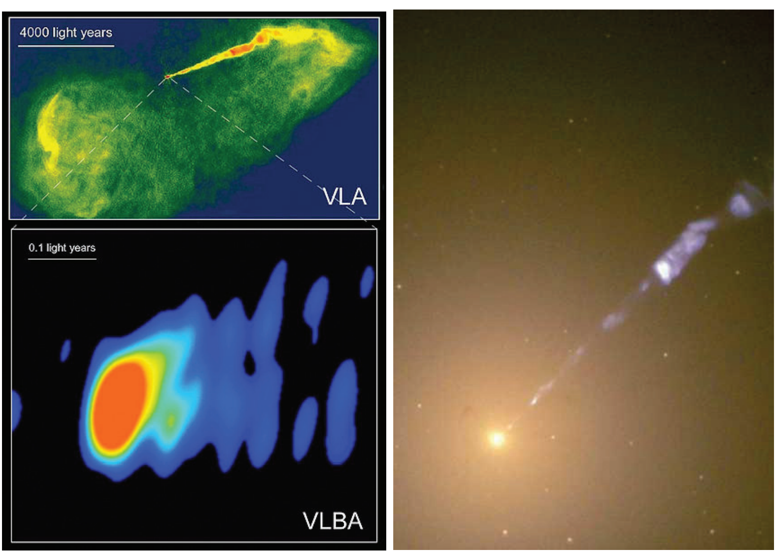


Figure 65: Interferometry with widely separated pairs of telescopes enabled radio astronomers to image the phenomena occurring close to black holes. At right is shown an optical image of M87 with Hubble Space Telescope.

Millimetre-wave radio astronomy

In addition to building larger telescopes to collect more signals, and pushing interferometric methods to obtain very fine angular resolutions, radio astronomers have also attempted to scan the sky in very short wavelengths, down to millimetres, as well. In 1970s, telescopes were built to study signals in millimetre wavelengths. Complex molecules tend to radiate energy in millimetre wavelengths (compared to atoms radiating in wavelengths of visible light, of a few hundred nanometres), and astronomers discovered a host of molecules in space. Microwaves are absorbed by water vapour in the atmosphere, and these telescopes had to be built atop mountains in dry area[2]. Since the wavelengths involved are small, the surfaces of these telescopes need to be made extremely accurately. A 30-m dish telescope was built in 1979 at Pico Valeta, Spain, among a few others around the world. Studies with these telescopes revealed the existence of giant molecular clouds, which are very dense and opaque to visible light, but which emit millimetre wavelength radiation from molecules like carbon-monoxide. Astronomers found that these molecular clouds, like the one we see in the Orion nebula, are the birthplaces of stars. The study of these objects therefore gives a glimpse of the earliest phases in the formation of stars.

A large array of telescopes is being set up in the Atacama Desert of South America. The *Atacama Large Millimetre Array (ALMA)* will consist of fifty or more telescopes to study millimetre and sub-millimetre wavelengths. At wavelengths below a millimetre, one reaches the border between

[2] The absorption of microwave by water is used in the concept of heating food in microwave ovens, since all food items contain water.

microwaves and infra-red in the electromagnetic spectrum. This region of the spectrum is difficult to study because of absorption by water vapour in the atmosphere. A 15-m telescope (*James Clark Maxwell Telescope*) was built at Mauna Kea in Hawaii in 1980s, to study sub-millimetre waves. It has since then discovered many distant galaxies, which are going through a burst of star formation, during which star light from young stars heat up dust grains which then re-radiate in these wavelengths.

Microwave background and cosmology

In 1991, a microwave telescope was launched to study the cosmic microwave background radiation in detail, aboard a satellite named *COBE (Cosmic Background Explorer)*. It measured the spectrum of the background radiation of the universe to a great accuracy and supported the predictions of the big bang model of the universe. This relic radiation comes to the Earth from the early phase in the history of the universe, when matter and radiation were packed so dense that they interacted with each other strongly. This interaction between matter and radiation stopped when the universe became about 300,000 years old, when it cooled down enough to be able to form atoms for the first time. Photons interacted weakly with atoms, and so they began to travel freely after this era. In other words, the study of the background radiation photons allows astronomers to study the universe as it was at the 'decoupling era', at the age of 300,000 years old.

Physicists have tried to understand the distribution of galaxies in the universe, and its evolution over time, with the hypothesis that the universe was initially rather uniform, but small non-uniformities got amplified by the action of gravity. If there was a slightly dense gas at a region, it would get denser with time, and the slightly tenuous regions would become even more tenuous. So the contrast between dense and tenuous regions would grow, and slowly structures would emerge in the universe. They predicted, from the data from optical studies of the distribution of galaxies at present, how the distribution of matter should have been at the decoupling era. According to Einstein's theory of gravitation, radiation coming from dense regions would be slightly 'red' or 'cold', having lost some energy in overcoming the gravity of the dense matter there. So, scientists predicted that the equivalent temperature of the background radiation of the universe (since it carries information of the universe at decoupling era) should show 'red' and 'blue' spots, arising from small inhomogeneities of matter at that time, which grew to become the present day structures in the universe.

COBE satellite found hints of this patchiness in the temperature, and another satellite (*WMAP: Wilkinson Microwave Anisotropy Probe*) launched in 2001 mapped this patchiness in great detail, with a resolution of about an arc minute. Another satellite, *Planck (*in honour of Max Planck, who studied the interaction between matter and radiation in late 19th century), was launched in 2009 to study this radiation in even finer detail.

At present, radio astronomers are planning to build an array of telescopes that will produce a collecting area of a thousand square kilometres, to be able to produce radio images of objects at larger distances than ever. They hope to be able to pin down the effects of evolution of galaxies by studying the emission of hydrogen atoms and ions in the interstellar regions of distant galaxies. Several countries are now pursuing different design concepts and building prototypes for this *Square Kilometre Array (SKA)* telescope.

11

Spaceborne telescopes — I

Our atmosphere challenges the capabilities of astronomical observations in many ways. Firstly, there are effects which tend to distort stellar images. However, these effects are rather temporary in nature, like temperature and other kinds of disturbances that produce twinkling, and they can be removed to a large extent by modern technology. Secondly, air also emits radiation in certain wavelengths, and this 'airglow' makes it difficult to observe very faint stars. But the most difficult limitations are however posed by the *absorption* of light by the atmosphere, as we have seen in the case of microwaves. The only parts of the electromagnetic spectrum that reaches the ground are *visible light* and *shortwave radio* signals.

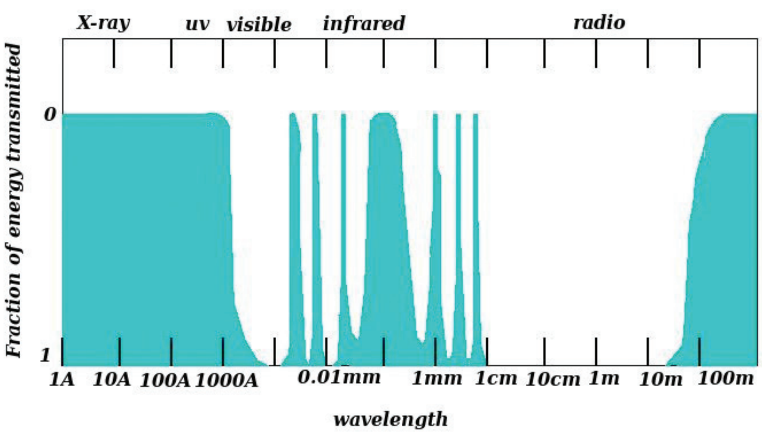


Figure 66: The fraction of incoming electromagnetic waves of different wavelengths that is transmitted through our atmosphere is shown with white colour in this picture.

The problem with long wavelength radio signals is that there is a sheath of electrically charged particles on top of the atmosphere, and the density of this layer is such that it does not allow electromagnetic waves that are longer than about 100 metres, and completely blocks out waves longer than about a kilometre.

On the other side of the electromagnetic spectrum, one has ultraviolet rays, in the range of 10-300 nanometres. Beyond ultraviolet, X-rays have wavelengths less than about a nanometre and gamma ray waves are shorter than this. These waves are also completely blocked by our atmosphere, and the only way to observe these waves from celestial objects is to put telescopes above the atmosphere.

Ultraviolet telescopes

After World War II, American engineers experimented with captured V2 rockets earlier used by Germany. The first attempt in 1946 of launching a rocket with a spectrograph to study the Sun went just above 150 kilometres before turning over. Subsequent launches showed that the Sun emitted X-rays and that its ultraviolet spectrum was different from its visible spectrum: there were bright emission lines instead of Fraunhofer absorption lines in it. These initial discoveries gave a boost to the idea that there was more to astronomical objects than was observed from the ground.

Further studies with the V2 rockets established that the Sun emitted a lot of radiation at a particular wavelength of about 121.6 nanometres, emitted by excited hydrogen atoms (called the Lyman alpha line). Astronomers were able to image the Sun in the light of this radiation in early 1950s, and within a decade, more than fifty stars were observed at wavelengths down to about 100 nanometres. The view of the sky in ultraviolet was very different from that seen with visible light: stars that are bright in ultraviolet are hot and massive stars. Other visibly bright stars, like red giants which have surface temperatures less than that of the Sun appeared dim in ultraviolet. The hot and massive stars are also very young stars, since these stars use their thermo-nuclear fuel very rapidly, and so when one can spot them, they are necessarily young. This implied that ultraviolet surveys of the sky picked up regions where stars had *formed recently*.

Most of these studies were done with the help of 10-15-centimetre-aperture telescopes sent aboard Aerobee rockets. They could only sweep across the target objects during the flight of the rocket, without being able to pinpoint the telescopes. By the mid-1960s, engineers were able to guide telescopes to observe specific targets, and this helped astronomers to gather data for a prolonged time. One could then record the ultraviolet spectra of stars, which contained signatures of some common elements that did not have any prominent line radiation in the visible wavelength range, like carbon and nitrogen.

The ultraviolet spectra of stars revealed not only the existence of atoms in the stars, but also the existence of atoms in the *intervening* medium— the interstellar gas, through which the radiation from stars travels on the way to Earth. This interstellar gas was found to be tenuous, far below any vacuum that was achievable in laboratories, and it contained elements like oxygen, carbon and so on, which were processed inside stars and ejected during supernova explosions. The first ultraviolet observations helped astronomers measure the abundance of these elements in deep interstellar space.

The status of spaceborne astronomy changed significantly when the Soviet Union launched an artificial satellite (*Sputnik-1*) in 1957. Satellites orbited the Earth continuously and allowed instruments on board to observe the sky in an uninterrupted manner, until the power supply in the satellite was over. A series of six satellites were launched by the Americans (the *Orbiting Astronomical Observatory*) between 1966 and 1972, with telescopes to observe ultraviolet and X-rays— the *OAO-3* was christened *Copernicus* to commemorate the fifth centenary of Copernicus's birth in 1972.

A sensitive spectrograph aboard *Copernicus* helped astronomers to discover the presence of a rare isotope of hydrogen in space. This isotope has an extra neutron in its nucleus, and is called deuterium. Deuterium is a fragile atom and is easily destroyed inside stars, and so all the deuterium found in the interstellar space is a relic of the era when minutes after the Big Bang (the origin of the universe) these nuclei were formed. The abundance of deuterium is also sensitive to the dynamical parameters of the universe, and the measurements done with *Copernicus (*of about fourteen deuterium atoms for every million ordinary hydrogen atoms) helped astronomers to study cosmology— the history and dynamics of the whole universe. The first results indicated that our universe was not dense enough to be able to counter its expansion with gravity, and that it would expand forever.

Then the *International Ultraviolet Explorer* (IUE) was launched in 1978 that carried a 45-cm aperture telescope. Instruments to study the ultraviolet rays are not very different from their optical counterparts: even an ordinary reflecting telescope with an aluminium reflecting surface can focus ultraviolet light. And the images can also be recorded with ordinary photographic plates, after adding a bit of gelatin which can absorb radiation shorter than 200 nanometres. The detectors aboard *IUE* were able to record photons from distant stars with wavelengths less than about 50 nanometres for the first time, and showed that violent winds swept out of many stars.

The uninterrupted view allowed by the orbiting satellite helped astronomers to monitor the fluctuations over time in the brightness of many quasars, and established that the extent of the source of radiation from quasars was small. The *IUE* was switched off in 1996, but it was fortunate to be working when a supernova went off in 1987 in a satellite galaxy of Milky Way, the brightest in the sky in the last century. Observations with *IUE* helped astronomers to identify the progenitor star of the supernova explosion. It also discovered a ring around it, caused by the meeting of the expanding shock wave and the gas that had left the progenitor star in the form of a wind prior to the explosion.

The *IUE* was also a pioneer in another aspect. The recorded data was analysed and kept within two days in an archive to be used by astronomers all over the world. This set a trend that has been followed by many space missions afterwards, opening up the sky for astronomers at large, and not keeping the data accessible to only a particular team of astronomers.

In 1983, the Soviet Union launched *Astron-1* with an 80-cm telescope, which remained the largest ultraviolet telescope for a decade until the Hubble Space Telescope was launched in 1990. The *HST* can detect photons down to about 115 nanometres. In 1992, a telescope was launched to explore even shorter wavelength radiation, between 10 to 100 nanometres, which is called extreme ultraviolet radiation (EUV). The telescopes launched earlier had studied extreme ultraviolet rays only from the Sun, especially the region just below the hot, outer periphery of the Sun, the corona. In these wavelengths, the Sun does not appear smooth as it does in visible light, but shows prominent spots of activity, where gas is being thrown up violently towards the corona.

Hydrogen atoms in space heavily absorb all radiations short of about 100 nanometres, and so it was initially thought that it would be difficult, if not impossible, to study distant stars below this wavelength. But actual observation showed that clouds bearing hydrogen atoms were not homogeneously distributed in the interstellar space, and that there were lines of sight in which the absorption by hydrogen did not block out all short wavelength radiation. In fact, the American Apollo spacecraft that performed a historic docking with a Soviet Soyuz spacecraft in 1975, carried a EUV camera that detected a few stars. It was however

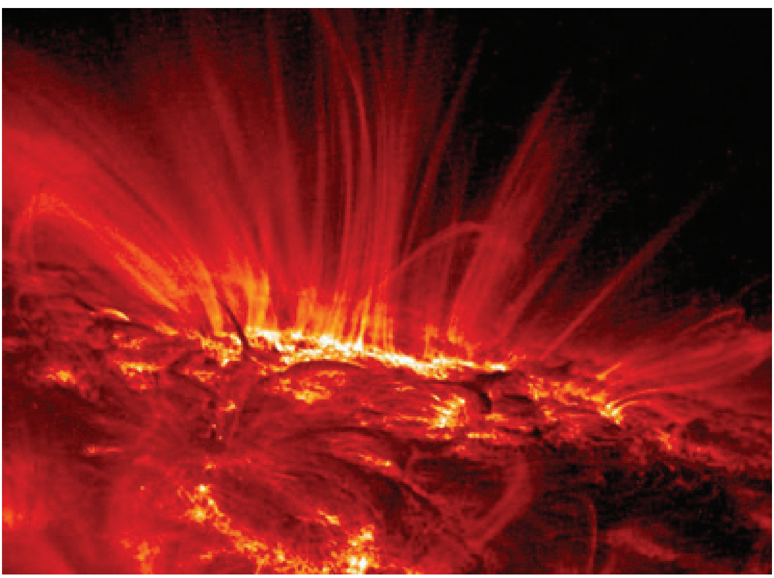


Figure 67: An ultraviolet picture of the surface of the sun, where gas is heated up and made to trace the magnetic field lines, during which they emit strong UV radiation, as detected by a UV telescope in space, named TRACE.

difficult to build EUV telescopes, as the designs are very different from that of optical telescopes, and similar to X-ray telescopes (see next chapter).

The most interesting discovery made in the EUV range was that of the hot gas in the vicinity of black holes in active galaxies. This gas, orbiting the black hole just prior to plunging into it, is very hot and mostly emits extreme ultraviolet light. Most of these photons are however absorbed either inside the active galaxies or in our Galaxy, but there were cases where clear lines of sight allowed these radiations to travel to the Earth.

A sensitive ultraviolet spectrograph was launched aboard a satellite in 1999. The *Far Ultraviolet Spectroscopic Explorer (FUSE)* telescope had a segmented mirror of four parts, and coated with lithium fluoride over aluminium for reflecting ultraviolet rays. The spectrograph was designed to study spectra around 100 nanometre range, and *FUSE* helped astronomer study deuterium in a great detail. After confirming the results of *Copernicus* telescope, that on average there were about fifteen deuterium atoms per million hydrogen atoms, *FUSE* also found that there were large variations in this ratio, which has prompted astronomers to investigate why this should happen.

Then *Galaxy Evolution Explorer (GALEX)* was launched in 2003, with a 50-cm aperture telescope, mainly to produce images in ultraviolet. Its images of distant galaxy showed regions where stars were being formed, and so it helped astronomers study the process of formation and building of galaxies. So far, *GALEX* has imaged about half a billion objects, and some of them showed cataclysmic events (which create high temperature gas that emits ultraviolet light) such as powerful winds from stars, or collisions between galaxies.

Infrared telescopes

On the other side of the electromagnetic spectrum, with wavelengths longer than that of the optical, lies another range of radiation that is also blocked by our atmosphere: the infrared, with wavelengths roughly between about 1,000 nanometres (1 micron) and 1millimetre, between the optical and radio waves.

Radiation in these ranges is emitted by relatively cool objects, and therefore offers a markedly different view of the universe than short wavelength photons do. One problem with studying infrared radiation coming from space is the absorption by the atmosphere, mainly by water vapour and carbon dioxide in the lower atmosphere. Another problem is that almost everything around astronomers, including the telescopes and people around it, radiate in these wavelengths. Even when the first problem is mitigated to some extent, by putting telescopes on mountains in dry places, the second problem remains. In fact, the steel support system for telescopes generates as much infrared radiation as a thousand stars.

After the discovery by William Herschel of infrared radiation from the Sun in 1800, astronomers did not get a chance to study the infrared sky in detail until in 1960s because of lack of suitable detectors. Infrared radiation is detected either through its *thermal* effect or the effect of its *radiation*. One can use a bolometer to detect it through the change in resistance in an electrical circuit due to change in temperature. There were some early attempts in the 19th century, using thermocouples (to record the change in voltage with temperature), with which Charles Smyth detected infrared radiation from the Moon in 1856. But infrared astronomy gained momentum in 1950s, when lead sulphide (PbS) cells were developed that recorded infrared radiation by the change in its resistance. In 1960s, more sensitive germanium bolometers were made, in which infrared radiation hit germanium strips, heated them and changed their conductivity. One needed to cool these detectors by liquid nitrogen, to decrease the amount of radiation coming from the detector parts themselves. Later, astronomers started to use detectors with semiconductors like indium-arsenide and mercury-cadmium-telluride, much in the same manner of PbS cells but with better sensitivity. These detectors are sensitive to photons with less than 10 micron wavelength.

With the development of array detectors like CCDs, astronomers have been using semiconductors that have energy gaps suitable for infrared photon energies, with an increase in sensitivity similar to the case in optical astronomy. These detectors can be made sensitive to large wavelength infrared photons, up to 100 micron.

The initial attempts at infrared astronomy began with ground based telescopes looking at near-infrared wavelengths (less than 10 microns), which do not suffer as much from atmospheric absorption as far-infrared light (about 100 microns). A pioneering catalogue of the infrared sky was charted in 1968 with the help of an 1.6-m telescope at Mount Wilson, USA. Gerry Neugebauer and Robert Leighton used PbS detectors, mostly sensitive for photons of wavelength near 2 micron, to discover more than 5,000 stars that had surface temperatures less than 2,000 degrees Celsius (compared to 6,000 degrees for our Sun). Then a 1.3-m telescope was installed in the early 1970s at Kitt Peak, USA, dedicated for near-infrared (and optical) studies, as well as a 1.5-m telescope at Tenerife, Spain. These telescopes had thin mirrors, and the secondary mirror was small, so that the support structure could be kept small (and so the radiation from the steelwork was small). The small secondary mirror could be tilted to and fro several times a second, so that the detector would alternately record data from the 'star and the sky' and then 'sky alone'. The radiation from the target star would then be measured by subtracting the latter image from the first one ([sky+star]-sky=star).

Figure 68: A balloon with an infrared telescope being flown on a balloon by astronomers from TIFR, India.

Later, bigger telescopes of this design were built on mountains. The Mauna Kea site at Hawaii is dry and is at an altitude of 4,200 metres, above much of the infrared absorbing water vapour. The 3-m *NASA Hawaii* telescope and the 3.8-m *United Kingdom Infra-Red Telescope (UKIRT)* were set up in the late 1970s. Besides these, all large optical telescopes at Mauna Kea and Chile are now fitted with near-infrared detectors.

Ground based telescopes are however not very useful for far-infrared studies of the sky, and one must send telescopes above much of the atmosphere to detect any significant amount of radiation. The initial work started with 16.5-cm telescopes mounted on rockets, by cooling the mirror structure and the detector. But these small telescopes were not very useful for long wavelength infrared radiation, since the angular resolution depends on the ratio between the wavelength the telescope aperture. Even at its best, the angular resolution of a 16-cm telescope for 100 micron radiation is about twenty arc minutes. Larger telescopes were then launched on balloons. In the mid-1970s a few 1-m aperture telescopes were launched from various places on balloons filled with helium and capable of carrying telescopes at an altitude of about 30 kilometres for several hours. In India, a 1-m far-infrared telescope was built and launched on balloons by a team of astronomers at the Tata Institute of Fundamental Research, Mumbai.

The next step was to put bigger aperture telescopes aboard aircrafts flying at high altitude. The *Kuiper Airborne Observatory* began operating in 1974, flying a 91-cm Cassegrain reflector designed to study infrared radiation between 1 and 500 micron range. It was instrumental in studying the rings of Uranus and the atmosphere of Pluto, as well as observing the signatures of various elements being

Figure 69: SOFIA carried an infrared telescope to the stratosphere.

produced during the supernova in 1987. In 2007, the *Stratospheric Observatory for Infrared Astronomy (SOFIA)* carried a 2.5-m telescope up to an altitude of 12 kilometres, to study near and far-infrared radiation.

The best way to observe the far-infrared radiation is of course from an Earth-orbiting satellite. The first spaceborne infrared telescope was launched in 1983. the *Infra-Red Astronomical Satellite (IRAS)* had a 60-cm aperture telescope, which was put inside a large jacket filled with liquid helium at a temperature of -257 degrees Celsius, the detectors being cooled to an even lower temperature. The mission lasted for ten months, as long as the liquid helium did not get evaporated. *IRAS* studied radiations between 8 and 120 micron, and discovered half a million infrared sources. One of the stunning discoveries made with *IRAS* was that of discs around stars like Vega and beta Pictoris, which were made of gas and dust, similar to the solar nebula from which the solar system originated. The discovery suggested that planetary formation should be a common phenomenon.

Infrared studies have one big advantage over optical observations in that it is not blocked by dust grains in space. The gas between the stars contains tiny grains of solid material, made of graphite, silicates and so on, with sizes ranging between about a hundred nanometres to a few microns. These dust particles absorb radiation in optical wavelengths, because their sizes are much bigger than the wavelength of these photons, but infrared radiation have longer wavelength, and can 'skirt' around these grains[1]. Infrared radiations can therefore reveal objects at larger distances than it is possible with optical light.

Dust grains have a crucial role in the formation of stars. These grains help molecules to form in interstellar space; the interstellar matter is otherwise too tenuous to form significant amount of molecules. Atoms can stick to large surfaces of dust grains and this process increases the chance of atoms meeting other atoms and thereby helps form molecules. Molecules, in turn, help gas to cool to low

1 Red light can travel further through the atmosphere on Earth than blue light in general, which is why the rising and setting Sun looks red, because the sunlight has to penetrate a larger distance through the atmosphere.

temperatures, and help gas to become dense, ultimately to form stars at the core of dense molecular clouds. These clouds are completely opaque to optical light, and only infrared radiation from the inner regions of these clouds can reach us. Therefore, infrared observations help astronomers to study the formation of stars. Astronomers used *IRAS* to study peculiar galaxies, called 'starburst' galaxies, which are producing stars in an immense burst of activity, and which are extremely bright in infrared light.

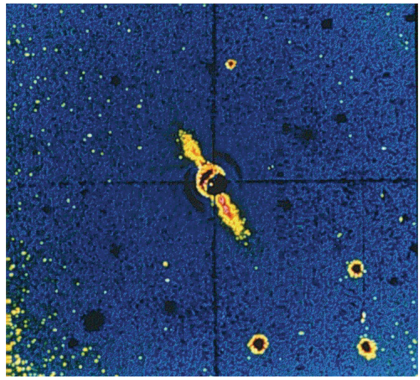


Figure 70: The dusty disc around the star beta-Pictoris as revealed by infrared radiation and detected by IRAS.

Also, since infrared light is not blocked by dust and gas, the infrared brightness of galaxies helps one to estimate the *total* amount of stellar material in it. Optical observations can reveal only a small fraction of its total number of stars. With infrared studies, astronomers can therefore measure the total mass of stars in a galaxy, and then estimate the total mass of galaxies. Studies with *IRAS* have helped astronomers to study the distribution of matter in the universe, and to compare this with the distribution of luminous matter as obtained from optical surveys, and then study the formation of galaxies in the universe.

After *IRAS*, the European *Infrared Space Observatory (ISO)* was launched in 1995, with a mirror of similar size as in IRAS, but with detectors thousand times more sensitive, and capable of detecting up to 240 micron radiation. Then the *Spitzer Space Telescope* was launched in 2003, with a 85-cm aperture telescope, and with detectors to study radiation between 3 and 180 microns. At about 8 microns, the telescope can give an angular resolution of about 2 arc seconds. With this unprecedented resolution, Spitzer was able to detect infrared radiation from even a tiny planet around a distant star. The existence of planets around a hundred stars had been established from dynamical measurements of stars, since the gravity of large planets can make the central star in a planetary system wobble. But this detection, in 2005, around a star named HD209458b was a direct detection and a concrete proof that planets existed around other stars.

The *Herschel Space Observatory*, with a large 3.5-m aperture telescope, and with detectors to study far infrared radiation, of wavelengths even up to 0.5 millimetre range was launched in 2009.

12

Spaceborne telescopes —II

At the shorter wavelength side, there are X-ray and gamma ray photons in the spectrum of electromagnetic waves. As wavelength decreases, the energy carried by a photon increases. The X-ray and gamma rays therefore carry the information about energetic phenomena in the universe. While infrared and ultraviolet views of the universe reveal sites of star formation, observations with X-ray and gamma rays often tell us about the end stages of the evolution of stars and about abnormal galaxies in which black holes wreak havoc and produce energetic radiation.

These short-wavelength photons are usually referred to by the energy they carry. This is partly because these photons are detected not much as continuous waves like optical photons but more like particles hitting a detector. A photon of wavelength of about a thousand nanometres has an energy of an electron volt (eV): it is equivalent to an energy acquired by an electron after being accelerated through one volt. Radiations with wavelength in the range of 0.01-1 nm, with energy in the range of 1-100 kilo electron volt (keV), are referred to as X-rays.

X-ray telescopes

The first studies in X-ray were done with V2 rockets after the WWII. It was found in 1949 that the corona of the Sun — the outermost layer of the Sun with tenuous gas at a million degrees Celsius— emitted a lot of X-rays. After these initial studies, American Aerobee rocket launches helped astronomers discover something surprising, and opened up a new vista in astronomy. In 1962, it was found that there were X-ray sources in the sky other than the Sun. It was previously thought, based on the extrapolations of X-ray luminosity of a star like the Sun, that other stars would not show any X-ray radiation at interstellar distances. The Sun was only a millionth as bright in X-ray wavelenghts as it is in the visible wavelengths. But astronomers, under the leadership of Riccardo Giaconni, discovered a bright source in the Scorpio constellation, which was named Scorpius X-1. This was the first X-ray source to be discovered outside the solar system. Then X-rays were detected from the Crab nebula, the debris from a supernova, and a diffuse X-ray background was discovered from all parts of the sky.

These launches allowed astronomers only snippets of the celestial phenomena. The total amount of time spent in actual observation until mid-1960s amounted to less than an hour in two decades. Also the rockets were unstable, and so the field of view of the instruments aboard them swept across the sky. In the mid-1960s, engineers developed methods to be able to point the instruments at a specific target for the span of the flight. It became possible to study the X-ray emission from different parts of the solar corona and also to compare the emission of the Sun during its active and passive phases.

Studies with X-rays were made difficult by the very nature of extreme short wavelength radiation. An X-ray telescope differs from optical telescopes in a fundamental way. X-rays do not reflect off the mirrors like visible light; they penetrate into the material of the mirror, since they carry much more energy than visible light. They behave like bullets hitting a wall, and it was impossible to bring X-rays into focus by any ‘lenses’. The earliest X-ray instruments did not have any device to allow a focussed view of X-ray sources. The detectors were kept open to the sky, with a collimator put in front of them, which was an array of metal bars, often arranged in a honeycomb design, to get a blinkered view of a small portion of the sky.

At the same time, since X-rays act like bullets, they can be made to graze along a surface like a bullet, and ricochet when they hit the mirror at a grazing angle. X-ray telescopes use this concept to bring the high-energy radiation into focus so that an X-ray source in the sky can be imaged. For this reason, X-ray telescopes look more like barrels than the familiar parabolic shapes of optical telescopes. Hans Wolter of Germany pioneered the design of such grazing incidence X-ray mirrors in 1950s, which was used by Giacconi to make the first imaging X-ray telescopes. The collecting power of these Wolter type telescope can be increased by mounting several tubes inside the tube of the first to gather and focus

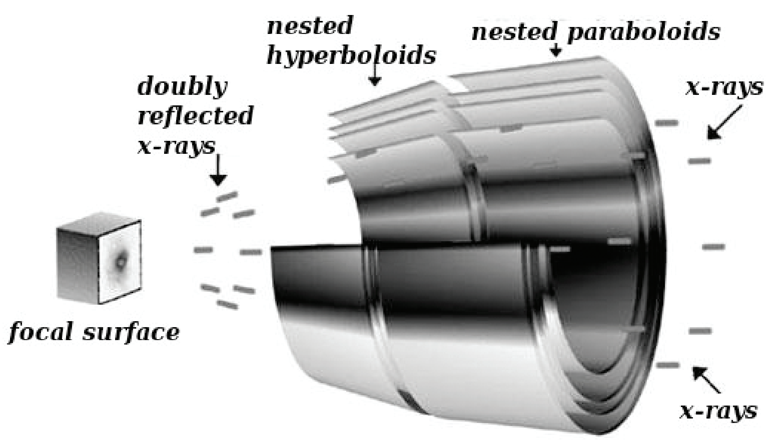


Figure 71: X-ray photons can be focussed after making them graze against metallic surfaces that are shaped like a paraboloid (and hyperboloid further inside). Several such tubes can be nested inside one another to collect a large number of X-ray photons.

radiation falling near the centre of the tube (which would be have been otherwise missed). One therefore has many surfaces nested inside one another.

After collecting the photons, one must be able to measure the position of the incoming photons so that one can build an image. The earliest detectors used a concept similar to that of a Geiger counter. These were often a chamber filled with gas, with two electrodes kept at a high voltage relative to each other. When an X-ray photon enters the chamber and ejects electrons from the atoms of the gas, these electrons in turn help dislodge many other electrons. An avalanche of electrons is thus created and they constitute a burst of electric current. The strength of the 'burst' is an indicator of the energy (and thus, the wavelength) of the original X-ray photon. These 'proportional counters' have been the usual instruments for X-ray detection over the years.

There are usually two types of instruments to create X-ray images. One type uses plates with millions of (micron sized) 'channels' in it, in which each channel acts as a separate photomultiplier tube, and creates an avalanche of electrons when X-ray photons penetrate them. These are called 'micro-channel plates'. One can also use semiconductor devices such as CCDs for X-ray imaging. In the last decade, another new idea has been used to image X-rays (and gamma rays). In this coded-mask telescopes, the top of the detector is a mask made of small blocks of lead or tungsten that blocks out incident X-rays. The blocks are arranged in a planned manner, so that when a X-ray source radiates on the telescope, it casts a shadow of the mask on the detector. Astronomers can then reproduce the image by measuring the position of the shadow, because the shadow pattern created by photons impinging the mask at different angles is different.

These X-ray telescopes have revealed the violent side of our universe. The X-ray image of the sky looks remarkably different from the optical image. Since X-ray photons have extremely high energy, they can be produced only by high energy particles. X-ray sources in the sky therefore signify regions where particles have very high energy, perhaps as a result of strong gravitational field, or catastrophic explosions, or intense magnetic fields. X-rays have now been detected from a large variety of sources, from the tenuous gas between galaxies to the vicinity of ultra compact objects like neutron stars and black holes.

After the *Sputnik* era, the first X-ray astronomical satellite was launched in 1970, named *Uhuru,* meaning 'freedom' in Swahili to celebrate the gaining of independence of a large number of African countries at that time. *Uhuru*, designed by Giacconi's team, carried two X-ray detectors, each 20-cm square, and it increased the number of known X-ray sources in the sky by a factor of ten. It recorded X-rays from the nearby Andromeda galaxy, as well as a distant radio galaxy, Centaurus A. It also found a number of X-ray sources inside our Galaxy, which were found to be binary systems of stars. One particular source, Cygnus X-1, appeared from its visible radiation to be a supergiant star without any visible companion star, although its orbital studies indicated the existence of a massive companion star, with

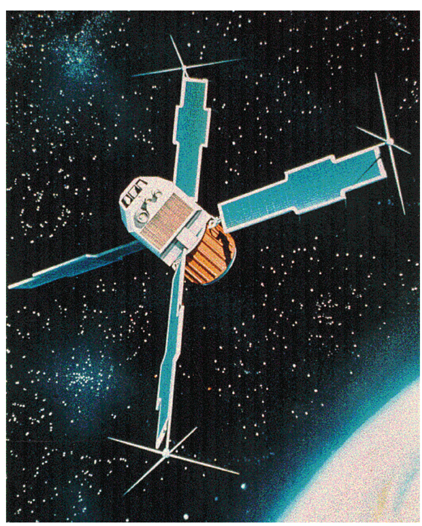


Figure 72: Uhuru was the first X-ray telescope in space.

masses many times that were normal for even a compact neutron star. Astronomers suspected that the companion was a black hole, and suggested that the X-rays were emitted by gas that was pulled away from the giant star by the black hole and was made to whirl around it before falling into it. Since then many confirmed black holes have been discovered.

Uhuru also discovered that clusters of galaxies emitted copious X-rays. These clusters of galaxies often harbour thousands of galaxies. The discovery of X-rays from these objects meant that they contain hot and diffuse gas in addition to the galaxies.

The next advancement in X-ray astronomy came about with launch of the *Einstein X-ray Observatory* in 1978 (also known as the High Energy Astronomy Observatory-2). It carried four nested X-ray telescopes, the outermost being 56-cm in diameter, and was able to image X-ray sources with an angular resolution of a few arc seconds. It was a big step compared to *Uhuru,* and it could reveal several individual X-ray sources inside the Andromeda galaxy, instead of a single blurry object. The *Einstein* observatory also discovered that nearby stars had corona like the Sun, and that quasars also emitted X-rays.

The European Space Agency launched *EXOSAT* in 1983, with an imaging telescope for X-rays of wavelength of about 1 nm, and detectors for X-rays of shorter wavelengths. It lasted for three years and astronomers used it to discover a curious phenomenon of 'quasi-periodic oscillations' from binary system of stars. The emission was not in regular pulses, but its detailed study revealed some cycles. This quasi-periodic oscillations in the X-ray emission still remains to be fully explained. *EXOSAT* also discovered the presence of iron in many X-ray sources: at a temperature of million degrees that are implied in the X-ray sources; iron atoms are stripped of their large number of electrons to become almost like a hydrogen or a helium atom, and they emit line radiation in the X-ray wavelengths. Later in 1987, '*Ginga*' (Japanese for 'Galaxy') launched by Japan discovered that the iron line radiation from active galaxies was often reprocessed by cold material near the black holes. The study of the emission from iron ions became a powerful tool for X-ray astronomers to study the properties of matter in the vicinity of the black holes that power active galaxies.

Then the *Roentgen Satellite (ROSAT)* was launched in 1990, and it surveyed the whole sky for X-ray sources, with a sensitivity that was a thousand times better than that of *Uhuru*. It discovered more than 60,000 sources, and discovered X-rays from neutron stars which were not part of any binary system. It also detected X-ray emission from the collision of Comet Shoemaker-Levy with Jupiter, and made a surprising discovery of X-rays from comets. Then the *ASCA (Advanced Satellite for Cosmology and Astrophysics)* was launched in 1993 by Japan[1], that carried four X-ray telescopes, each with 120 nested surfaces (of aluminium foil and coated with gold), which allowed imaging with a resolution of about an arc minute. ASCA was significant for its capability of resolving the X-ray spectrum into finer details with the use of CCDs, achieving a resolution of a few percent in wavelength (which meant an ability of discovering lines as narrow as one hundredth of the wavelength at which it appeared). With this unprecedented mix of angular and spectral resolving power, ASCA was able to discover the effect of Einstein's general relativity on photons emitted by iron ions near black holes in active galaxies. Photons coming out of the intense gravitational

[1] ASCA also means 'flying bird' in Japanese.

field of black holes lose a part of their energy, a direct prediction of Einstein's theory. This loss of energy, by different amount for photons coming from different locations in the vicinity of black holes, broadens the line radiation, and the nature of broadening is a tell-tale signature of the gravitational effect on photons.

ASCA also helped discover X-rays from high-energy particles on the periphery of a supernova remnant (SN 1006). These high energy particles had been predicted by the theory of supernova explosions, in which shocks are driven in to the surrounding gas, accelerating particles to high energy. This was the first time though that the existence of these high energy particles (called 'cosmic rays') were revealed directly. *ASCA* was also able to resolve line radiation from different elements in the hot gas in clusters of galaxies, and found the abundances of different elements, like sulphur and oxygen. These elements could only be synthesised inside massive stars, and could not be produced by the tenuous gas permeating the galaxy clusters. The existence of these elements therefore implied that gas with these elements was thrown out by galaxies into the intergalactic space.

Since many energetic phenomena are transients or cyclic in nature, it is also instructive to study the arrival time pattern of X-rays from these sources. The *Rosse X-ray Timing Explorer (RXTE)* launched in 1995 have discovered many interesting aspects of binary system of stars with compact companions, like neutron stars or black holes.

Then in 1999, two large X-ray telescopes were launched: the *Chandra X-ray Observatory* (paying homage to the astrophysicist Subramanian Chandrasekhar) by NASA, and the *XMM-Newton* (X-ray Multi-Mirror Mission) by the European Space Agency. *Chandra* has four sets of nested mirrors, with surface so smooth that the largest deviations on it are less than a nanometre. Its angular resolution is about half an arc second, rivalling the resolution of the Hubble Space Telescope in visible light. It has a high-resolution camera that uses micro-channel plates, and there are also accurate spectrometers to distinguish between X-rays of different wavelengths. *XMM-Newton* has a larger field of view than *Chandra* and so it has been able to image extended features of X-ray sources.

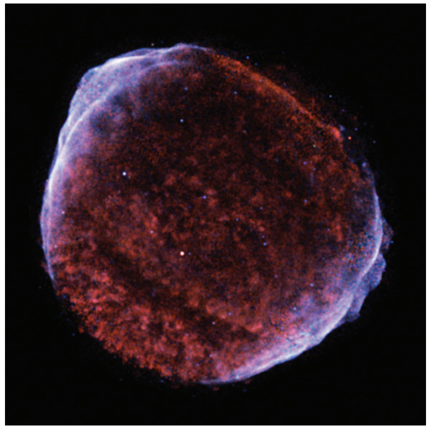


Figure 73: The supernova remnant SN1006 as seen in X-rays emitted from energetic particles being shocked by the expanding shell of debris from the stellar explosion, imaged by CHANDRA.

Among the many discoveries made by *Chandra* and *XMM-Newton*, the most notable are the discovery of X-rays from the region near the black hole at the centre of Milky Way, of the effect of active galaxies in clusters on the X-ray emitting hot gas with the image of ripples of shocked gas, and of fine details of the inner regions of Crab nebula. Astronomers have used *Chandra* to study the effect of collisions between clusters of galaxies in which invisible dark matter gets separated from the X-ray emitting gas, and thereby proving the existence of dark matter.

Together, these telescopes have put X-ray astronomy—with fine details of X-ray images and spectroscopic information— at the sophisticated level of optical astronomy. What took almost four centuries for optical astronomy to develop from the Galilean telescopes to the Hubble Space

Telescope, was achieved within a span of mere five decades in the field of X-ray astronomy.

India plans to launch a satellite *ASTROSAT* to study the X-ray universe in 2010, with a set of large area proportional counters, a coded-mask detector to monitor the X-ray sky, and a host of other instruments, including a ultraviolet telescope to supplement the X-ray data.

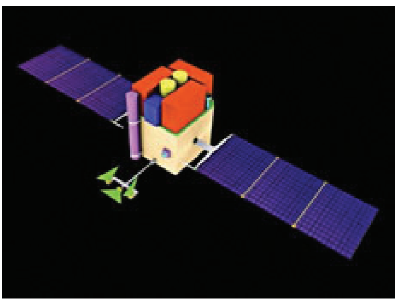


Figure 74: The Indian satellite ASTROSAT will have X-ray instruments and a UV telescope.

The spectacular success of the last few X-ray satellites has encouraged astronomers and engineers to plan for a bigger telescope in space. Now NASA, ESA and JAXA (Japan's Aerospace Exploration Agency) have come together to plan for a joint *International X-ray Observatory* (IXO), for which scientists are studying various design concepts. It is likely to extend the range of X-rays to be studied to shorter wavelengths, with capabilities of imaging X-rays down to 0.05 nanometres, and is bound to discover even more violent side of cosmic objects.

Gamma-ray telescopes

The gamma-ray region of the electromagnetic spectrum comprises radiations below about 0.01 nanometres, with photons that carry energy of about 0.1 million electron volts (MeV[2]). The most common gamma-ray detector is the

[2] 1 MeV is the energy that an electron acquires after being accelerated through one million volts.

scintillation detector, which convert these energetic photons into visible light. Usually they have a large crystal of sodium iodide. When a gamma-ray photon hits the atoms in the crystal, it loses energy in the form of visible light, which is then amplified by surrounding photomultiplier tubes. One then needs to put a device over the detector that would allow radiation from a small region of the sky, so that it can act like a telescope.

Theoretical studies by scientists prior to 1950s predicted many different phenomena that would produce gamma rays. One of the first gamma-ray observations were done in 1961, with detectors aboard a satellite named *Explorer 11*, which detected a diffuse gamma-ray background emission from all over the sky. Theoreticians had expected such a background emission from the interaction of high-energy particles with gas between the stars, the interstellar matter. Gamma-ray astronomy gained momentum after *OSO-3* detected gamma-rays from many celestial phenomena in our Galaxy in 1967. Then *SAS-2* and *COS-B* satellites were launched in 1972 and 1975, by NASA and ESA respectively. The *COS-B* telescope had spark chambers and tungsten foils: when a gamma-ray photon hits the nucleus of a heavy atom like tungsten, it creates a pair of electron and positron, which are detected by a scintillation detector. From the tracks of the electrons and positrons in the spark chamber, it was possible to estimate the angle of incidence of the original gamma ray photon.

Early generation gamma-ray telescopes like the *COS-B* had poor angular resolution, of only about two degrees (four times the angular size of the Moon), but the first discoveries were significant. The regions of our Galaxy that appeared bright in *COS-B* maps were the dense clouds inside which new stars were formed, like the molecular cloud in Orion constellation. Also, it discovered gamma-rays from pulsars in Crab and Vela nebula.

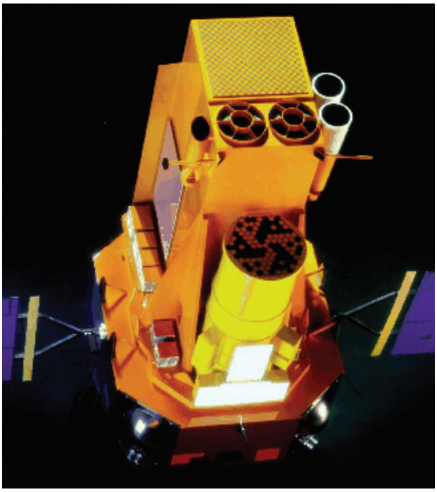


Figure 75: The INTEGRAL mission that used a coded-mask to produce gamma-ray images (the mask pattern can be seen on the top of the tube near the bottom of the assembly).

Then in 1991, the *Compton Gamma Ray Observatory* (CGRO) was launched (named after Arthur Compton, who had pioneered the study of interactions of energetic photons with matter). It had two imaging devices, to image the sky in gamma rays from 1 to 30 MeV, and between 20 and 30,000 MeV, with a resolution of about a degree. Then a coded-mask gamma-ray telescope was launched by ESA in 2002. This telescope, named *International Gamma-Ray Astrophysics Laboratory (INTEGRAL)*, achieved an angular resolution about ten arc minutes, and produced a detailed catalogue of gamma ray sources in the sky. One of the most important results obtained with the help of these telescopes was to map the regions in Milky Way that has a radioactive isotope of aluminium, with atomic number 26, which has a life-time of about a million years. This element is ejected into the interstellar space by massive stars during supernova explosion, and since it decays after about a million years, it helps astronomers estimate the rate at which stars are being formed in our Milky Way.

Perhaps the most exciting discovery in the field of gamma ray astronomy came from defence satellites launched in 1960s to monitor the compliance of nuclear test ban treaty, since nuclear bomb blasts would necessarily produce gamma rays. A series of satellites named Vela recorded some flashes of gamma rays, but then it was realised that they came from outer space and not from any nuclear test on Earth. These gamma ray bursts (GRB) lasted from a fraction of a second to minutes and faded away afterwards. The sources of GRB remained a mystery for decades, because with the early generation of gamma-ray telescopes it was not possible to pinpoint their location in sky and then identify them with objects seen in visible light.

CGRO found in the 1990s that these bursts took place uniformly over the sky, and hinted at sources that were very distant and outside our Galaxy. Theoretical studies predicted that giant explosions that could emit the gamma rays in bursts, would glow in radiation in longer wavelengths at a *later* time. It was predicted that there would be an 'afterglow' in X-rays, optical and then radio wavelengths after the initial, brief gamma ray burst. Then a X-ray telescope (named *BeppoSAX*) launched in 1996 first detected the X-ray afterglow of a gamma ray burst, and with the better angular resolution achievable in X-rays, it was able to point towards potential sources of gamma ray bursts.

Later, many gamma ray bursts were followed up with X-ray and optical, and even at radio wavelengths. The *Swift Gamma-Ray Burst Mission*, launched in 2004, has helped astronomers to track these bursts within minutes at other wavelengths. It is a multi-wavelength observatory with a gamma-ray, X-ray, ultraviolet and optical telescope. It now appears that at least one kind of gamma-ray bursts, ones that linger for a minute or so, are caused by the collapse of very massive stars in distant galaxies.

Recently, the *Fermi Gamma-ray Space Telescope* was launched in 2008 to study gamma rays in a wide range, with wavelengths ranging between 0.1 and 0.000 000 004 nm (corresponding to photon energy of 0.3 billion MeV). It has

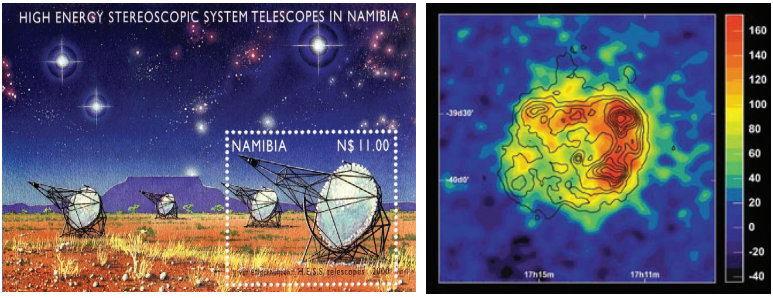


Figure 76: Namibian postage stamp showing the HESS telescopes. On the right is a TeV photon image of the supernova remnant RX J1713.7-3946, with an angular resolution of 3 arc minutes.

a telescope that should achieve an angular resolution of a few arc minutes for the highest energy photons, and is likely to discover many new energetic phenomena in space.

Astronomers have tried to detect even higher energy photons, with energy of about a TeV (Terra electron volt= 1 billion MeV), using our own atmosphere in an ingenious manner. It would require very heavy instruments in space to detect these photons, but there is another way. When such high energy photons penetrate our atmosphere, they create a 'shower' of secondary particles, which travel through air with a speed larger than that of light in this medium. As a result, they emit optical or ultraviolet light, called Cerenkov radiation, in a manner similar to the sonic boom of a supersonic aircraft. These flashes can be detected by ordinary telescopes designed to pick up faint and transient flashes. They are faint— with only about ten photons per square metre for a 0.1 TeV photon, and they last about a nanosecond. Although very-high-energy particles also produce air showers, but there are differences between them and the showers created by a TeV photon.

The *Whipple Telescope* in USA, with a 10-m telescope built in 1968, was the first telescope to observe TeV radiation. The

HEGRA (High Energy Gamma Ray Astronomy) on the Canary Islands recorded the most energetic photon (with about 15 billion MeV energy) from an extraterrestrial source till date, from an active galaxy named Markarian 501. Another telescope on the Canary Islands, *MAGIC (Major Atmospheric Gamma-ray Imaging Cerenkov Telescope)*, uses a 17-m aperture reflecting dish, and observes photons with energy at TeV range.

In 2004, the *High Energy Stereoscopic System (HESS)*, with four telescopes to detect Cerenkov radiation, was built in Namibia. With data from four telescopes, scientists can accurately estimate the direction of high-energy gamma rays, accurate to about an arc minute. One of the impressive results from *HESS* was the image of a supernova remnant RX J1713.7-3946, showing photons with 10 TeV being emitted by cosmic rays accelerated by the expanding shockwaves, just as theoreticians had predicted, and it was consistent with the X-ray observations of supernova remnants.

13

Cosmic-ray and gravity-wave telescopes: modern astronomy

A completely different view of the universe is provided by a different kind of 'radiation' that is not an electromagnetic wave like light. Cosmic rays are highly energetic *particles* that bombard the Earth constantly from outer space. They were discovered in 1912 by Victor Hess during a balloon flight when he found that there was some kind of 'radiation' that was powerful enough to dislodge electrons from air molecules, and that this 'radiation' level *increased* with altitude. Later it was established that these 'rays' came from outer space and they were named 'cosmic rays'.

These cosmic rays essentially consist of fundamental particles, like electrons, protons and nuclei of different elements, and their energy spans between a billion electron volts (10^9 eV) to more than a billion times that (to about 10^{20} eV). They are highly energetic compared to a typical air molecule on Earth, which have about 0.025 eV, and have been a puzzle for scientists ever since they were discovered. What accelerates these particles to such high energies, and why are they so numerous? For particles with a billion electron volts, there are about a thousand particles hitting every square metre every second. The distribution of energy among these particles is also very curious. When a hot object emits photons, most photons carry a *typical* energy[1]. But there

[1] Although some photons are radiated as well with somewhat more or less than the typical energy.

is no 'typical' energy for cosmic rays: there are particles with a huge range of energies, only that they become rarer with higher energy.

Astronomers now know that most of these cosmic rays are produced in explosive events in space. When a massive star uses up its fuel to run thermo-nuclear reactions to produce light, its core collapses to form a compact star, while the rest of the star is disrupted in a catastrophic explosion that hurls its material into space with a tremendous speed, about ten thousand kilometres per second. This explosion sends a shock wave through the surrounding gas, and accelerates the gas particles to extremely high energy. These 'cosmic rays' then travel around the galaxy and bombards the Earth from all directions.

Cosmic rays of the highest energy must come from other galaxies, as they cannot be confined within galaxies by any means. Apart from stellar explosions, cosmic rays are also produced by the energetic jets from black holes in active

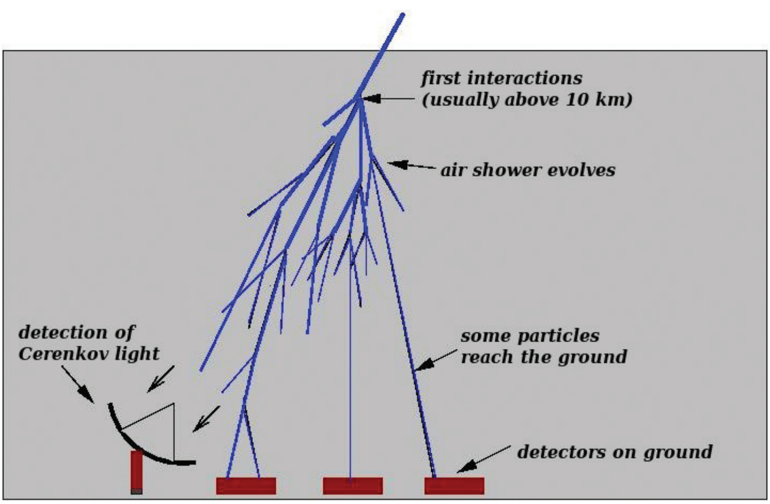


Figure 77: Different types of detectors are used to record data from air showers produced by an incoming cosmic ray.

galaxies. Cosmic rays therefore carry information of violent astronomical events in space.

Low-energy cosmic rays are absorbed by our atmosphere, and so they must be detected by balloons and rockets sent to high altitude. Cosmic ray particles with higher energy can be detected on Earth by two means. When a high-energy cosmic ray hits the upper atmosphere, it creates a jet of particles with slightly lower energy than the original particle, and which travel roughly in the same direction. The particles in this jet can in turn create more particles of lower energy when they hit other molecules in air. This 'cascade' of particles, called an 'air shower', grows until particles in the shower have lost their energy and have been absorbed in the atmosphere. A high-energy cosmic ray can generate a shower with a million particles in it, depending on the energy of the original incoming particle. Pierre Auger discovered these air showers in 1937, and in the same year,

Figure 78: The Fly's Eye observatory in Utah, USA, observes Cerenkov radiation from cosmic rays crossing different parts of the sky.

Homi Bhaba and Warren Heitler worked out the theoretical aspects of this process.

The secondary particles in the air shower emit flashes of blue, Cerenkov light (as we have learned in the case of energetic gamma rays, which also create air showers). This flash can be detected by optical telescopes, and the data can be used to interpret the energy and direction of the primary cosmic ray.

The secondary particles in the shower also eject electrons from air molecules during their passage and excite some molecules like nitrogen. These excited molecules then radiate visible or ultraviolet light, called 'air fluorescence'. This radiation can be detected by optical telescopes, especially on clear, moonless nights. These flashes however last only a few microseconds, and one needs to use fast camera elements. The *Fly's Eye* detector at Utah desert, USA, was installed in 1977, with a number of modules, each comprising a spherical mirror of 1.6-m in diameter and a dozen photomultiplier tubes at its focal surface. The modules were oriented so that the whole assembly— acting like the compound eye of a fly— can observe all parts of the sky. When an air shower passes through the sky, its trajectory is measured by the firing of photomultiplier tubes one after another in a succession. In 1986, a second assembly was installed at a distance of 3.4 kilometres from the first, and together one could view the sky in a 'stereoscopic' manner, making the reconstructions of the air shower trajectories more accurate.

Very high-energy cosmic rays can produce showers with billions of secondary particles that are energetic enough to reach the ground, and which can be detected by particle detectors. These detectors are often arranged in the form of a grid or an array on the ground so that a single shower can be detected at several points. One can then use the information about the number of particles hitting a certain detector in this array, and the time of detection, to re-create a model of the air shower and therefore estimate the direction and energy of the original cosmic ray.

The *Haverah Park Array*, built in 1967 in UK, was one such detector assembly. Recently, the *Akeno Giant Air Shower Array (AGASA)* in Japan detected some ultra-high-energy cosmic rays, with energies more than a billion billion electron volts. The observations of these ultra-high-energy cosmic rays pose a challenge to their understanding. Theoretical studies predict that such highly energetic particles cannot travel through the intergalactic space for distance larger than about 150 million light years, because the cosmic microwave background radiation drains their energy as they pass through it. This implies that sources of these ultra-high-energy particles must be nearer than 150 million light years, but it is not clear if there are enough potential sources within this distance.

Figure 79: A water tank detector in the Pierre Auger cosmic ray observatory.

Astronomers have now built a large cosmic ray telescope in order to study these particles in detail. The incidence of these particles is rare, with only about one particle hitting a square kilometre area in a whole century. Therefore one must build a large-area detector assembly. A grid of detectors is now under construction in Argentina, covering an area of 3,000 square kilometres. It has been named *Pierre Auger Cosmic Ray Observatory*, and will consist of different types of detectors, to record Cerenkov radiation from secondary particles and then to detect them on ground by their interaction with water. These ground detectors will consist of 1,600 water tanks, each containing 12,000 litres of water. When cosmic ray particles pass through them, they will emit a radiation which will be detected by sensitive instruments around the water tank. By 2007, this observatory recorded twenty seven ultra-high-energy cosmic ray events and found that their directions were indeed related to the general distribution of galaxies in the vicinity of Milky Way, implying that these cosmic rays did come from nearby external galaxies.

Neutrino telescopes

An even more 'invisible' messenger from the cosmos is a tiny particle called neutrino, which was discovered in 1956. Its existence was hypothesised in 1930, but the actual discovery was delayed by the fact that it hardly interacts with any other particle. Neutrinos can pass through solid blocks of matter without interacting much with its constituent particles, leaving any record of its passage, and therefore they are hard to detect. The only way to increase the number of interactions is to increase the amount of matter it is made to pass through. It was finally discovered by monitoring with photomultiplier tubes in a tank with 200 litres of water with dissolved cadmium chloride, whose molecules are excited by the passage of neutrino and which then emit flashes of light. This light flash is called scintillation, and these type of detectors, scintillation detectors.

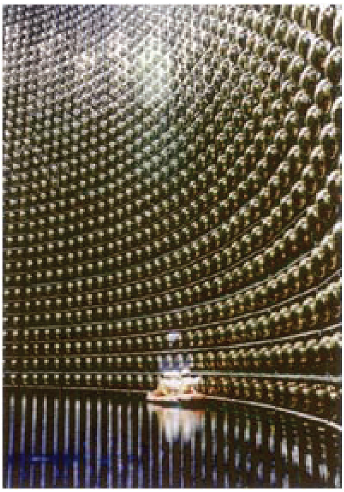


Figure 80: The Kamiokande neutrino observatory had photomultiplier tubes on the walls of a tank with a kiloton of pure water.

Any attempt to detect neutrinos from outer space is further compounded by the fact that cosmic ray air showers also create neutrinos as secondary particles, and any detector system would be swamped by this 'noise'. So neutrino observatories have to be installed deep underground. The first attempts to build such detectors began at Kolar Gold Field in India and in East Rand mine in South Africa in the 1960s. They detected the signatures of atmospheric neutrinos that were created on the other side of the Earth and had passed through it. Then in 1980s, Cerenkov detectors began to be built, which were more sensitive than scintillation detectors. The Irvine-Michigan-Brookhaven detector in a salt mine in Ohio, USA and the Kamiokande detector in Japan had tanks with thousands of tons of purified water, monitored by photomultiplier tubes. These two detectors made the dream of neutrino astronomy possible when they detected about twenty neutrinos from the supernova in 1987 in a satellite galaxy of Milky Way.

Then Super-Kamiokande was built in Japan with 50 kilotons of water, and the Sudbury Neutrino Observatory came up in a nickel mine in Canada, with a kiloton of water.

These two detectors solved a long-standing puzzle of neutrinos from the Sun, and helped confirm what astronomers had inferred about the Sun. The radiation emitted by the Sun is produced in its core, with the help of thermo-nuclear reactions. The core is very hot, with a temperature of about fifteen million degrees Celsius, and at this temperature, four protons can fuse together to form a helium nucleus which is slightly less heavy than four protons weighed together. The mass difference is radiated away in the form of light— initially gamma rays at the core but which get degraded in energy as it passes through the body of the Sun and finally emerges as visible light.

A by-product of the fusion reaction is neutrinos that travel almost freely through the material inside the Sun and reach the Earth. The observation of neutrinos from the Sun can therefore be a tool to study the core of the Sun which is otherwise opaque to all other kinds of radiation. The initial measurements made by neutrino detectors found that there was a *shortfall* in the count of neutrinos from the Sun by a factor of *three*. So there was either a mistake in the knowledge of the temperature and density of the solar core, or there was something wrong with neutrino detection. It was however pointed out that there were three types of neutrinos and the initial detectors only collected neutrinos of one type. It was possible that neutrinos changed

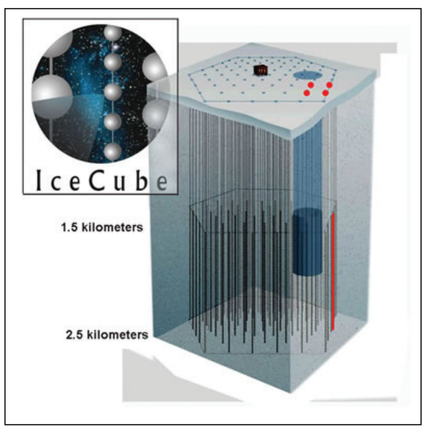


Figure 81: The IceCube neutrino observatory at the South Pole will consist of strings of photomultiplier tubes hung through kilometre-long holes dug in ice, to detect Cerenkov radiation from neutrinos passing through ice.

from one type to another during their journey to the Earth. To test this hypothesis, one needed to build a detector that would record all three types of neutrinos.

Observations with the Super-Kamiokande and the Sudbury Neutrino Observatory finally confirmed in 2001 that neutrinos did *change* from one type to another, and that the estimate of the temperature and density of the core of the Sun made by the astronomers were correct after all. An almost invisible particle had helped astronomers prove what they had inferred from studies with the visible light.

Encouraged by these observations, scientists have been planning to build even bigger neutrino observatories. In the 1990s, a detector was set up in Lake Baikal, and another, near the South pole at Antarctica, with strings of photomultiplier tubes deployed inside kilometre-long holes in ice. A bigger telescope is now under construction in the Antarctica, called the Ice Cube neutrino observatory, which will use a kilometre-cube of ice as the target material, to be monitored by about five thousand detectors put on 80 vertical strings. It is likely to be operational by 2011 and will try to detect neutrinos from gamma ray bursts and active galaxies, and further broaden the horizon of astronomical observations.

Gravitational- wave astronomy

Perhaps the most elusive of all cosmic messengers is the gravitational wave. In Einstein's theory, gravity is not considered a force between objects as Newton had thought. A massive object does not pull other objects by the force of gravity, but it distorts the structure of space around it. (One should say 'space-time', to be precise, since time and space are intimately connected in Einstein's theory.)

Ordinarily, we view space as being three dimensional, with a geometry in which parallel lines never meet. In the new theory, Einstein proposed that space could be *curved* and its geometry could be that of the surface of a ball or a saddle, in which the parallel lines either converge or diverge from one another. He considered that the effect of a massive object would be to distort the geometry of space, and therefore change the trajectory of other objects embedded in this distorted space. So our Earth does not orbit the Sun because of the pull of gravity, but because the gravity of the Sun has distorted the space to the extent that Earth's trajectory in it has become curved, instead of a straight line. Even light would travel in a curved line in such a distorted space-time, and Einstein's prediction of the bending of light around the Sun was proved to be correct during a solar eclipse in 1919.

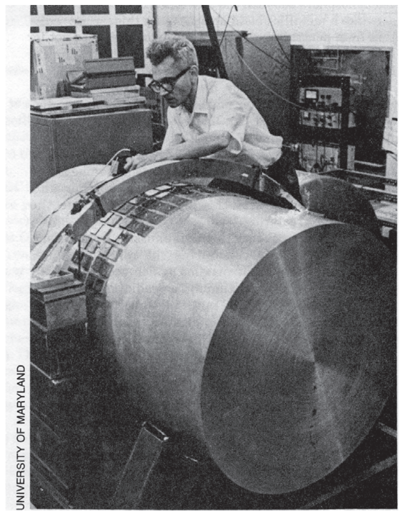


Figure 82: The bar-detector for gravitational waves built by Joseph Weber.

This view of gravity predicts that a moving object would cause ripples in the space-time around it, just as a moving charge particle excites electro-magnetic waves around it. A moving object would therefore emit 'gravitational waves'. That such waves should exist, was discovered indirectly by radio astronomers studying a binary system of pulsars (PSR 1913+16). Joseph Taylor and Russell Hulse carried out accurate observations over many years and discovered that the pulsars were coming closer to one another, by an amount that was predicted from Einstein's theory, since they would lose energy by emitting gravitational waves as they orbited one another.

This ripple passing through space-time would cause the distance between objects to increase and decrease during the passage of the wave. The fractional change in distance is likely to be extremely small, of about one part in a thousand billion billion (10^{21}), and changing several times a second, even for the strongest possible waves. This implies a change of a billionth of a nanometre in the distance between two objects kept at a kilometre apart. The detection of such minute differences is a technological challenge, and was considered almost impossible for a long time. The first attempts were made by Joseph Weber at the University of Maryland, USA, using sensors stuck on the surface of a cylinder of aluminium that was cooled in vacuum, but it turned out that it was not sensitive enough to detect gravitational waves from space.

Physicists have now built sensitive instruments based on the concept of interferometry. When the light from a source is split into two parts and then made to combine again, there would be interference between the two trains of waves and the result would be a 'fringe' pattern, of alternately dark and bright regions. This pattern is sensitive to the difference in distance travelled by the two trains of waves, and can be used as a tool to measure small changes in distances. If gravitational wave passes through a region in the path of a laser light that has been split into two and made to combine, then one could hope to measure the tiny difference in the travel time of one of the trains of light, provided all other sources of 'noise' are take into account.

Such a *Laser Interferometer Gravitational-wave Observatory (LIGO)*, using laser radiation, has recently been built in the

USA. It consists of two interferometers, separated by a distance of 3,000 kilometres. In each interferometer, laser light is made to travel a distance of 4 kilometres several times before coming together to combine at a detector. *LIGO* is designed to detect a fractional change in the distance as small as one part in 10^{21}, and oscillating about a hundred times a second, which is expected if a gravitational wave hits the system, coming from a catastrophic event like the violent mergers of two massive black holes. Any such detection will supplement the data from electro-magnetic radiation.

As a matter of fact, even a non-detection will help astronomers in disproving certain theories. For example, one of the hypotheses for the origin of gamma-ray bursts for short durations has been the collision between two massive

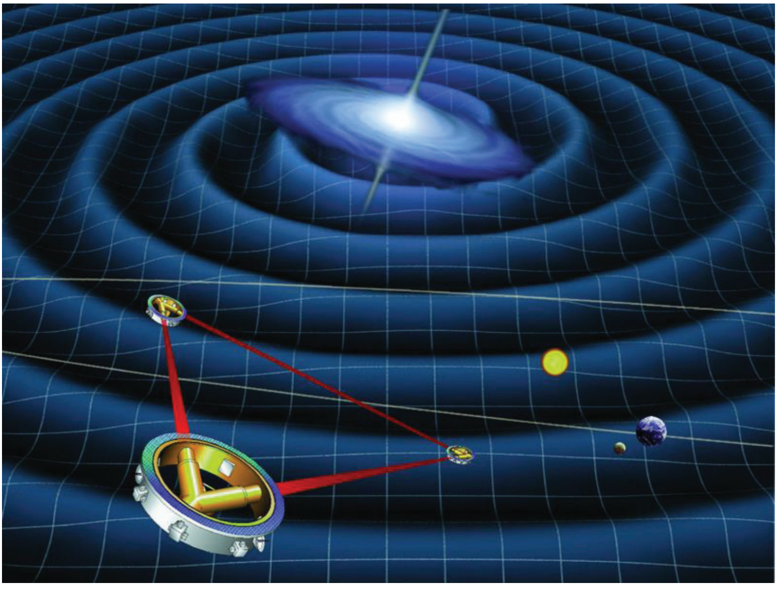


Figure 83: Artist's conception of gravitational waves emanating from a distant active galaxy and hitting the detectors aboard LISA, a system of three spacecrafts to be launched in 2020.

neutron stars or black holes. *LIGO* failed to detect any gravitational waves from a short gamma-ray burst in February 2007 (GRB070201), and it seems to have ruled out the hypothesis of merger of compact objects.

Scientists have proposed to put an even more sensitive detector in space. NASA and ESA are planning to launch a detector with three spacecraft in orbit around the Sun, which will try to detect in a different frequency band than *LIGO,* and will therefore complement it. If launched in 2020 as scheduled, this will split laser light into two trains that would travel a distance of 5 million kilometres before combining again, and should be able to detect the tell-tale signatures of extreme violent events in the universe.

Multi-wavelength astronomy

The progress of astronomy with telescopes since the time of Galileo can be best judged by the different types of telescopes modern astronomers use. There are telescopes for visible light, and then 'light' of different wavelengths, from energetic gamma and X-rays to long radio waves. Modern astronomers also use 'particle telescopes' to study cosmic rays and other particles like neutrinos from space. And then there is the exciting possibility of detecting oscillations in the geometry of space itself.

What have astronomers achieved though by making bigger telescopes, better detectors and opening up the window of observations to hitherto 'invisible' rays? On the one hand, big telescopes and sensitive detectors have brought the farthest corners of the universe to our doorsteps in two ways: collecting more radiations than earlier generation telescopes, thereby making faint objects visible, and by revealing finer details of distant objects. On the other hand, telescopes operating at different wavelengths have helped astronomers to study different aspects of cosmic objects.

Radiation of different wavelength coming from a single source can tell astronomers about the different physical aspects of the object. Photons of different wavelengths are produced by different physical processes, and their study can reveal the underlying reason behind these processes, and so astronomers can get a wholesome idea by studying an object with radiations of different wavelengths. In a sense, using only one wavelength to study an object is like a blind man's perception of an elephant. It is far from being a complete picture.

Ancient astronomers had to confine their study to optical radiation, but modern astronomers have access to a wide range of data, from short to long wavelength photons. Consider the following example of studying a distant galaxy with light of different wavelengths. If one looks at a spiral galaxy like ours with optical light, one finds normal stars like our Sun, or dimmer and orange-red stars. In ultraviolet, however, the galaxy may look very different, because only hot, massive and very young stars would show up in the ultraviolet image, specifying the regions of the galaxy where new stars are being formed. In infrared, one would detect re-radiation from dust grains that are heated by these hot and young stars. A comparison between the optical, ultraviolet and infrared images would show the difference between star formation in the past and present, and therefore, would provide a clue to the history of star formation in this galaxy.

The X-ray image would reveal the existence of binary stars that exchange gas, which becomes hot in the process and emit powerful X-rays. In radio wavelengths, one would be able to detect neutral hydrogen atoms that would

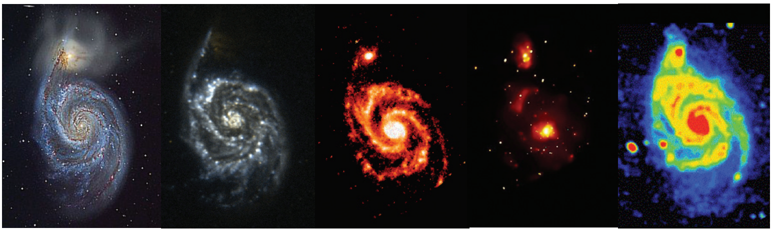


Figure 84: The galaxy M51 (Whirlpool galaxy) as seen in optical, ultraviolet (GALEX), infrared light (ISO), in X-ray (Chandra) and in radio (VLA).

delineate the cool regions of the interstellar space in that galaxy. Radio observations may also reveal unusual activities spurred by black holes, or processes in which energetic electrons are ejected in the forms of a jet and which then radiate in radio wavelengths. Some energetic particles accelerated in these processes may even traverse the intergalactic space and show up on Earth as cosmic rays.

Modern astronomy has thus progressed not only by building bigger telescopes and better detectors, but also by trying to detect photons that were thought 'invisible' even a century ago; it's not just about bringing near the far, but also detecting what was once considered invisible.

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Eyes on the Sky: The story of telescopes

1609 was a watershed year in the history of science. Spectacle makers found that a certain combination of lenses made distant objects appear closer. Galileo Galilei made a telescope of his own and looked at the stars with it. And what he found changed the way mankind thought about Nature.

Since then astronomers have built bigger and better telescopes, to view the universe in ways never thought possible before, in different 'colours' of light, visible, infrared, radio, X-ray and so on, and even with the help of particles. Now they are even building telescopes to detect waves in space-time.

This book chronicles the history of telescopes in easy language and with many illustrations. It explains what drives astronomers to build big telescopes, how engineers help them with technological innovations and how the findings with these telescopes have enriched our mind.

About the author

Biman Nath is an astrophysicist at the Raman Research Institute, Bangalore. He received his PhD in astronomy from the University of Maryland, USA, and he does research on cosmology and the evolution of galaxies. He has written several popular science articles and books.

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