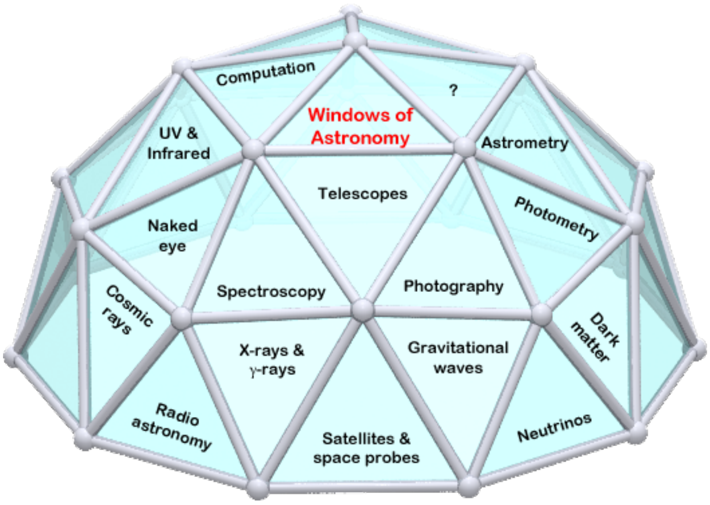
Windows of Astronomy

Introduction



You walk slowly around a picture gallery. Within each frame on the walls is the artist's interpretation of a view, incomplete in detail and incomplete in representing what is beyond the canvas. No special training is needed to see the pictures but the knowledgeable will gain more from the visit. That experience is a good metaphor for this piece. My gallery is the view outwards from the Earth.

The stars and planets have surely been discussed since there has been language to do so. The records of astronomy, though, date back only some three millennia. For most of that time, all that our ancestors had were their naked eyes. As we can now say, an object the size of a golf ball with a small hole in it is a woefully inadequate tool for exploring the universe, even when connected to an enquiring mind. Being generous, it's perhaps not surprising in retrospect that cultures all over the world got the Universe at large wrong. Naked eye vision is one very small window on the Universe. Within the last half millennium mankind has discovered windows unimagined by our ancestors that each give a new view of the universe at large, adding a wealth of knowledge to the overall picture. This piece is my brief look through fifteen windows on the universe. Little background knowledge is assumed. If any of these brief summaries encourages you to look for more detail in authoritative astronomy sources, they will have been worth writing. No references are included but enough use is made of technical words that finding up-to-date information should be quite easy.

The naked eye


Looking at Mercury. Image by Sophie Desrosiers

What can you do with the naked eye? When it comes to the stars and planets, not a lot. The eye can observe the stars twinkling, a bit like the flames in a fire seen from afar. It's natural to infer something is burning and, feeling no heat, that they are a long way away. They are far away but they are not burning, as we now know. Indeed, would that we could reproduce on Earth their means of generating energy continuously. The Sun, Moon and five 'stars' move relative to the rest, so they are probably nearer. The Sun certainly influences the Earth on a daily basis; the other wanderers were assumed to as well. Another wrong assumption, except for the Moon, but that not in the way imagined before the 17th century.

The pattern of the wanderers against the backdrop of 'fixed stars' could be measured approximately, the time for the wanderers to go around the sky determined. This much astronomy was pretty well only a handmaiden to astrology. Eclipses were seen intermittently, interrupting the daily regularity. It's easy to see that the stars are not equally bright and a sharp eye notices that a few change their brightness but such detail was seldom mentioned. The fixed stars provided some assistance with navigation but only as a consequence of their positions and visibility. To make matters even worse, we live at the bottom of a deep ocean of air that distorts starlight, bends it, absorbs some of it and for half the time so dazzles us with scattered sunlight that we can't see either stars or planets.

In truth, our ancestors learnt almost nothing about the stars from naked eye observation beyond the fact that they existed and the Earth was not alone. They wove mythological stories around the patterns of stars in the sky; they imagined that deities with power over us lived in the heavens; they told creation myths for the world. There aren't too many options for creation myths. Hindu cosmology involves circles of time with no beginning and no end. This is a natural extrapolation from the cycle of days, years and the life and death of generations. Most cosmologies seem to start with darkness or chaos before one or more deities introduce light and order. Not a shred of observational evidence supported any of the beliefs. This is not to say our ancestors were naive or had any choice. Had I lived in naked eye times I would no doubt have chanted the chants, praised the deities and repeated the myths. There were often serious consequences for not doing so. There wasn't much more that could be done when it came to trying to understand the universe at large.

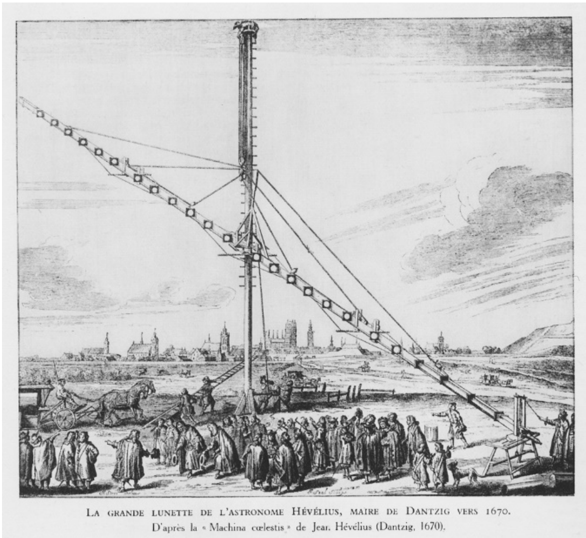
Telescopes

Given the dire state of naked eye astronomy, the telescope deserves all the praise it is given. Yes, there were instruments before the telescope. Some were finely made and allowed positional measurements to be recorded to better than one tenth of a degree. Among the notable instruments were Arabic astrolabes, mural circles and variants of the quadrant and celestial globe. The observations of the great astronomer Tycho Brahe were all taken before the invention of the telescope. They allowed more precise models of the motions of the planets to be invented but they didn't tell his contemporaries or immediate successors anything more about what planets or stars were.

Even the simplest telescopes made an immediate impact. In the early 1600s, Galileo famously wrote about the myriad of stars fainter than naked eye vision could detect, about the Moons of Jupiter, sunspots and the changing phases of Venus. This was real evidence, not speculation. In the following century Robert Burns famously used the line: *facts are chiels that winna ding.* He wasn't talking about astronomy but simply emphasising that there is no escaping evidence. Any understanding of what is out there must be based on evidence. Galileo's evidence was a crushing blow for astronomy by assertion. As his life story showed, the old guard generally took their ideas to the grave.

For at least the first century of telescopic astronomy, the instruments themselves were optically imperfect and mechanically flimsy. Nonetheless, the genie was out of the bottle. Less than perfect was hugely better than nothing. The Moon was mapped in some detail, Mars seen to have polar caps, the great spot of Jupiter followed, Saturn found to have moons and rings, comets understood to be in the realm of planets, not the high atmosphere. The first detailed star charts were drawn up and double stars recognised, even though not at that time appreciated to be binary systems.

By two hundred years after Galileo, the realisation had dawned that telescope optics need to be mounted within precision mechanics. One of the early discoveries with the new breed of precision instrument was the finding of the first asteroid by Piazzi in Sicily at the start of the nineteenth century. This was Ceres, now deemed large enough to be a dwarf planet. Greater changes were to come. A second realisation that took hold in the nineteenth century was that to see further one needed a wider telescope to collect more light, not one with greater magnification. The technology of making larger glass lenses improved a lot but refracting telescopes reached their technological limit in the second half of the century at about 1 metre diameter. From then on, larger telescopes meant reflecting telescopes.



17th century telescopes varied from short and small to long and unwieldy

21st century instrument. One of four 8.2 m telescopes at Paranal, Chile. Courtesy ESO.

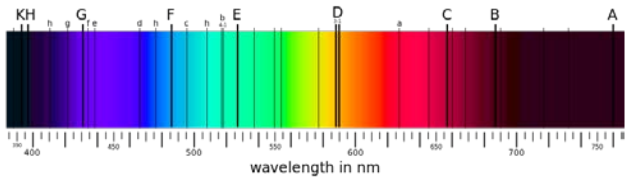
Seeing more stars meant seeing further. Did the supply of stars ever run out? Apparently not in the nineteenth century. So, was the universe infinite or in some way localised? Seeing more also meant seeing that not everything out there is a star. Messier had charted about a hundred fuzzy objects in the late 18th century. How did these fit into the scheme of things? Were they truly fuzzy objects like giant gas clouds or simply tight clusters of stars like a swarm of bees seen in the distance? Answering this question also drove the quest for '*more light*'. Did the universe at large have structure? Just how far away are the stars in any case? Whatever the answers, they would be provided by evidence, not rhetoric. Bessel began an answer by being the first to measure the distance to one of the nearest stars using the precision astrometric tools of the 1830s. The nearest stars are over 250 thousand times as distant as the Sun, itself 150 million km away. That is only the first rung on a distance ladder whose length would not be well established for a further century and half.

Of course we are still in the telescope age and this instrument is as important as ever in astronomy. Twenty-first century telescopes are as different from their nineteenth century predecessors as those were from 17th century versions. New observatories being equipped today can expect 8 – 10 metre diameter instruments with computer controlled positioning, image correction and digital image detection. They will also have adaptive optics to sharpen small field images and active optics to compensate for objective mirror distortion as the orientation of the telescope is changed. The instruments may well be operated from consoles thousands of kilometres away, though there will be on-site technicians. Even amateurs now expect computer controlled positioning and digital image processing. A few telescopes over 20 metres diameter will see their first light in the 2020s.

Discoveries made with the telescope today are not made with an eyeball peering closely through a brass-mounted eyepiece. What singles out a modern instrument is the specialist equipment that is planned with it, specialist equipment that opens new windows. Three of the most important windows are those of *spectroscopy*, *photography* and *photometry*, all of which were introduced in the 19th century.

Spectroscopy

A laboratory spectroscope is an instrument that spreads out the spectrum of a light source, typically by means of a prism or a diffraction grating. The idea for such an instrument was developed by the famous glass-worker Joseph Fraunhofer in the second decade of the 19th century. With his spectrometer he was able to see detail in the solar spectrum that isn't visible in such naturally occurring phenomena as rainbows, detail that even Isaac Newton had missed during his experiments with prisms. As later spectroscopists found out, the detail was in the form of dark absorption lines, characteristic of the elements present in the outer layers of the Sun and characteristic of their state of ionisation. This work opened the window of stellar spectroscopy.



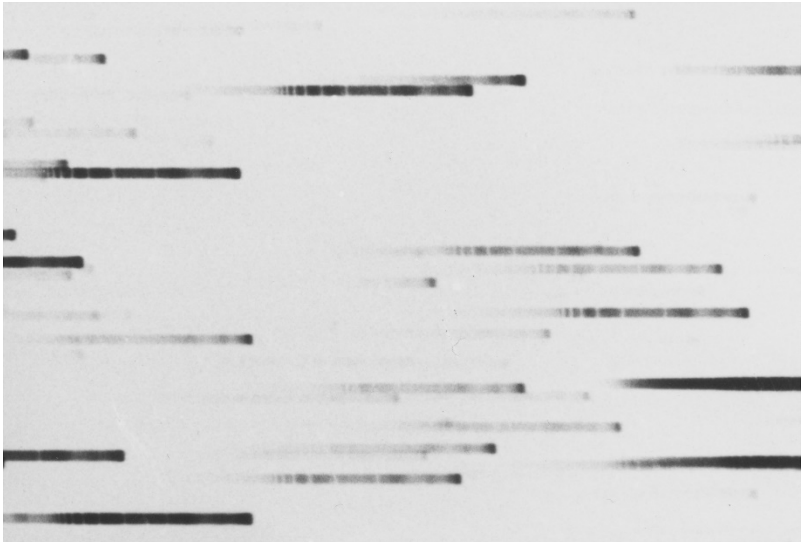
Solar spectrum courtesy Wikipedia

Stellar spectroscopy turns out to be an astonishingly powerful tool. It achieves what nineteenth century philosophers and indeed non-astronomers thought would be impossible, namely telling what stars are made of. Through spectroscopy one can deduce the composition of a star, its temperature, the presence on its surface of strong magnetic fields, even its speed of movement towards or away from us and, for very distant objects, their rough distance away. This list is not exhaustive. Spectroscopy is in a way the astronomer's microscope, revealing detail far beyond that accessible to our unaided senses. One unsung result of spectroscopy is that the stars for as far as we can see, and that is a very long way indeed, are made of the same elements and particles as are found on Earth. The strangeness of the heavens is the variety of ways these ingredients are organised, making Earth a rather special place.

Since motion of a star has a small effect on the positions of its spectral lines, binary stars show a well-defined periodic motion of their spectral detail as they orbit each other. Many binaries 'give themselves away' by showing doubled spectroscopic lines even if we don't see two stars. This allows the period of their orbit around each other to be deduced, the eccentricity of their orbits and at least the ratio of their masses. Since the mid-1990s, the same general technique applied to the lines from a single star has been used to detect orbiting planets. It is the most reliable technique for identifying 'extra-solar planets'.

There are broadly two spectroscopic techniques, both begun in the nineteenth century. Placing a large narrow-angle prism in front of the objective lens of a refracting telescope creates a spectrum for every object seen. Narrow angle prisms don't have much dispersion so the spectrum does not show fine detail. Moreover, if many stars appear close together in the image, their spectra will overlap. Nonetheless, this method provides far more detail than simple observations of the colour of a star and enables stars to be classified into a range of types. At first the significance of the classification wasn't apparent but in the twentieth century the classification was shown to be related to their temperature and to the evolution of stars over time.

The second method is to place the spectrometer at the eyepiece end of the telescope and display and record the spectra of individual stars or galaxies. This can be done with spectrometers that give a much wider spread to the spectrum than objective prisms and hence show more detail. A development of this technique at the end of the twentieth century was to position fibre-optic receptors at the known position of stars or galaxies in the final image plane. The fibre-optics transmit the signal to individual channels in a display that records each spectrum digitally. In the twenty-first century version, many hundreds of spectra are obtained simultaneously as the telescope follows the rotation of one patch of sky and the fibre-optics are then manoeuvred under computer control when a new image is selected. It is this technique in particular that allows astronomers to plot the large-scale structure of the universe, for each distant galaxy in a field of view reveals how far away it is through the wavelength of its spectral lines.

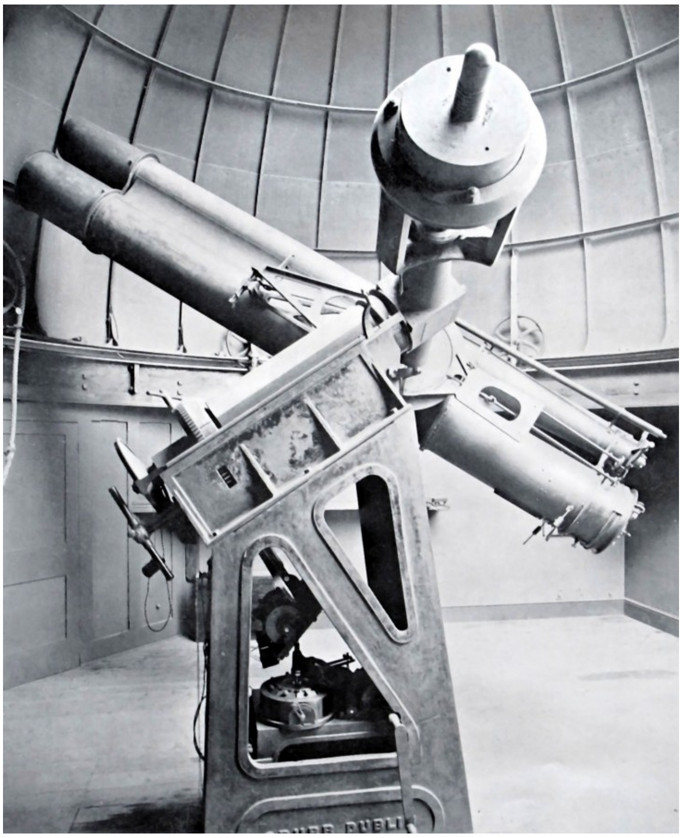


Part of the field given by an objective lens prism. Colour is not necessary to see the spectral lines. Because of the spread of light by the prism, only brighter stars in the field show a clear spectrum.

Photography

Following experiments by Nicéphore Niépce and Fox Talbot in the 1820s, photography became a commercial proposition in the hands of Daguerre in the 1830s. Even by mid-century, photographic plates were extremely insensitive ('slow'). The only astronomical photography possible in the 1850s was imaging the Sun and Moon. In spite of their brightness, these objects demanded exposures of minutes. In the early 1870s the chemistry of photography changed from the 'wet collodion' process, where plates were prepared in liquid just before the exposure, to 'dry plates' that could be prepared well in advance so long as they were kept in total darkness. Dry plates were being made that were increasingly fast, allowing star fields to be imaged. Exposures could still be 20 minutes or sometimes longer.

Keeping a telescope pointing directly at the stars as they moved around the Earth so that the image on a photographic plate did not move by the width of a dot was at first beyond the accuracy of telescope tracking clockwork of the time. New telescope drives were developed but even with them the observer generally had to look through supplementary optics and keep a chosen star exactly on cross-wires. This led to the development of the 'astrographic telescope'. It was essentially two telescopes strapped together, one for a large photographic plate and one with an eyepiece for the observer. Taking good photographs in the nineteenth century and into the twentieth century still required a sharp eye and a lot of patience.



David Gill's astrographic telescope in South Africa

David Gill, an Aberdonian who was Her Majesty's Astronomer at the Cape of Good Hope, made the first photographic star catalogue in the 1880s to 1890s with the assistance of Jacobus Kapteyn of Leiden University. This contained over 450,000 stars down to 9th magnitude, about a twentieth of the brightness of the least visible naked eye stars. The catalogue took some 10 years to prepare, which was only about a quarter of the time a comparable northern hemisphere catalogue had taken using 'eyepiece astronomy'. Photography was clearly the tool of the future and Gill in collaboration with over 20 other observatories embarked on a whole-sky catalogue including stars a hundred times fainter than the earlier survey. Photography would be the key to finding what was out there beyond the range of the eyepiece.

Photography revealing Messier's faintly seen blur M83 as a spiral galaxy 15 million light years away. Courtesy ESO.

Photography made it very clear that some nebulous objects in the sky were gaseous and some were star clusters. With photography, other galaxies were discovered and the Milky Way seen to be simply our neighbourhood in the suburbia of the 'local cluster'. Galaxies in the Universe have turned out to be as common as stars in the Milky Way and the oft-quoted figure is that there are more of them than grains of sand on the Earth. Galaxies are not all the same size nor all the same shape. How the population of galaxies that we observe today has come about is an unfolding story in astronomy.

Glass backed photographic plates were used until well into the second half of the twentieth century. They were more stable than film. Towards the end of the twentieth century photography changed rapidly from chemistry to physics. With the advent of CCD detectors (charge coupled devices), fields of view were divided into pixels and images directly recorded digitally. The new technology preserved the fundamental strength of photography, namely that the camera accumulates the effects of generally faint light over the whole exposure time. Eyeballs just respond to the illumination of the moment. With the new digital technology has come digital image processing that further increases the information recorded in each image. Photography still provides the foundation of astronomy, with many other techniques adding a wide range of detail to our knowledge of the universe at large.

Photometry

A section of the sky around the Pleiades showing that stars vary in brightness. Before the advent of electronic measurements, the relative brightness of stars in an image was estimated by their sizes on the photographic plate. In this image, the intrinsically brightest stars are exciting nearby gas that adds extra blue nebulosity. Courtesy NASA.

In the second century BC, the Greek astronomy Hipparchus described stars in three brightness categories. The basis of the modern system of magnitudes, in which a range of about 6 magnitudes covers stars visible to the naked eye, is attributed to Ptolemy some 300 years later. Ptolemy may have flagged brightness variation as a fact but no-one seemed to give it much significance or query the reason why stars varied in brightness. Of course the brightest stars featured in navigation and astrology but the ‘why’ question didn’t seem to be on the agenda. Even when stars fainter than could be seen with the naked eye were discovered in the seventeenth century, for over a century very little attention was given to measuring stellar brightness.

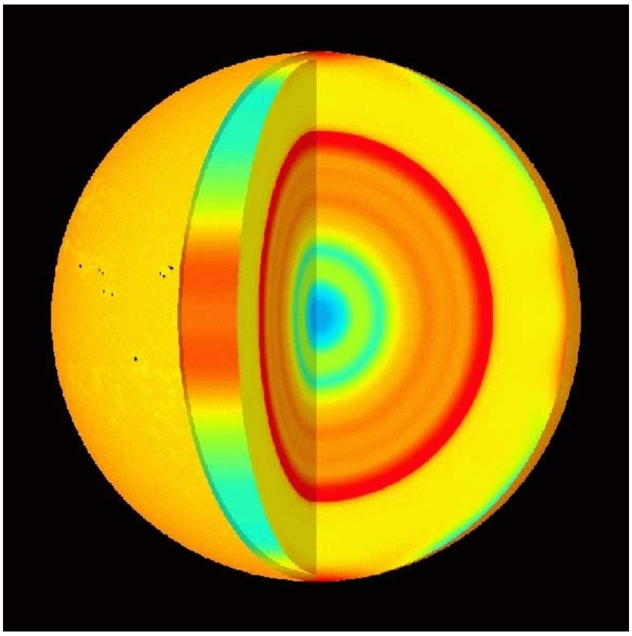
Recognising that our sensitivity to brightness is logarithmic, Pogson in the 1850s set up the ‘modern’ magnitude scale, with 5 steps corresponding to a brightness change of 100. This makes 1 step correspond to a difference in brightness of the fifth root of 100, namely 2.512. Like Honours degrees, the smaller the number the more brilliant the star. Yes, it would have been better if stellar magnitude had been called 'stellar faintness'. So much for the theory. By Pogson’s time it had been recognised that all stars were not equally far away and distance would affect how bright a star appeared. Increasing the distance by a factor of 10 would decrease the brightness by 100 and increase the magnitude designation by 5. It would turn out that distance is not the biggest influence on brightness. The biggest influence is temperature. A star 10 times hotter than the Sun (and a few are) has a radiant output 10,000 times that of the Sun, though a lot of that is in the ultraviolet.

Determining distance from a star’s brightness you need to know its temperature. The hotter a star, the bluer it is. A simple way of estimating temperature has been to measure the brightness (magnitude) of a star through a blue filter (calling the result B) and measure the same star through a green filter (call it V for visible). The difference B-V is the colour index, quoted for many catalogued stars. Colour index is related to a star’s temperature and its spectroscopic type (referred to above under ‘spectroscopy’). You get more precise information with a spectroscope but it’s a quick and comparatively simple method to characterise individual stars.

More subtle is the variability of stars. Unlike our Sun, many stars are variable in their output. The change in the magnitude and the timespan of the change separates different types of star. For some Cepheid Variables there is a close link between the period of the changes and their intrinsic brightness (called absolute magnitude). This makes them ‘standard candles’, a key to deriving stellar distances out to some 10 million light years. The photometric properties of ‘type 1A supernova’ have also been recognised as standard candles and have allowed distances beyond 1000 million light years to be found. Yet another case of variability is that caused by planets transiting across the face of a star. It is through photometry that we now know of the existence of thousands of extra-solar planets around other stars.

Brightness has three important connections: distance, temperature and variability. How is brightness measured? It can be estimated by eye by comparing with a light of known brightness but it is basically a photometric quantity that can be measured electronically. Curiously enough, infrared sensors were developed before optical ones. Seebeck discovered the thermoelectric effect in 1821 and thermopiles followed in the next decade. These produced a detectible electric current when one side is slightly heated. The discovery in the 1870s that the resistance of selenium varied depending on how much light was shone onto it was the beginning of electronic photometry. Later, photocells were constructed so that the photoelectric material sealed in a vacuum tube emitted a current (of electrons) when illuminated. Nowadays, photocells use solid state circuitry, usually based on silicon.

It’s hard not to overuse the word ‘astonishing’ when describing the techniques employed and the knowledge found by astronomers. If the 19th century non-astronomer was astonished that the detailed composition of stars could be found (by spectroscopy), the 21st century non-astronomer may be equally astonished that astronomers can determine the internal structure of stars. I haven't seen this done but it seems very likely that a detailed analysis of the sound of a bell will allow someone who hasn't seen the bell to deduce in quite fine detail its size, variations in shape and thickness and even some of its flaws. Stars are huge but they also ring. We can't hear them since sound doesn't travel across the near vacuum of space and



Helioseismometry, courtesy NASA/ESA. Concentric layers in a cutaway image showing oddities in the speed of sound in the deep interior of the Sun, as gauged by two instruments on the SOHO probe.

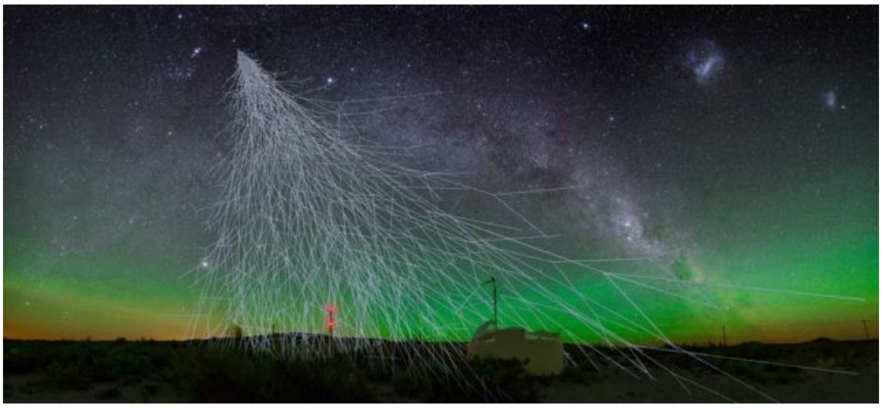
instead of vibrating several hundred times a second they ring more nearly at one vibration in a thousand seconds. How a star rings is determined by its internal structure so if the spectrum of its modes of oscillation can be determined then we learn about its internal structure. Astonishing! Two methods are used to probe the ringing. One is very precise photometry. The other is very careful examination of the fine motion of stellar spectral lines. The Sun can be examined in fine detail (helioseismology) and stars in less detail (asteroseismology). There are 'spin off' determinations of stellar sizes and ages.

Cosmic rays

Cosmic rays are a discovery of the early twentieth century. Credit is given to Victor Hess, earning him the Nobel Prize for Physics in 1936 'for his discovery of cosmic radiation'. Hess and others had been puzzled by why charged electroscopes spontaneously discharged wherever they were, inside the laboratory or outside a building. Radioactivity had recently been discovered at the end of the nineteenth century as a source of ions that could be responsible for such a discharge. Radioactivity was suspected to be the culprit. Around the year 1912, when he was working in Vienna, Hess made a number of balloon ascents with his electroscope. He showed that an electroscope discharged faster the higher he went. By 5 km altitude (a height where breathing unaided is difficult) his electroscopes discharged several times faster than at ground level. Hess's experiments were quite dangerous but they showed convincingly that the source of ionizing radiation came not from the ground but from outside the Earth. Where it came from was a tough problem to solve.

Nowadays electroscopes are not needed to detect cosmic rays. Switch on a Geiger counter and the click-click-click at the rate of a few a second comes mostly from secondary cosmic rays. The direction of cosmic rays can be explored with a cosmic ray telescope that contains a line of particle detectors (3 is enough) that give a signal only when all are triggered in rapid succession. Such telescopes showed that there was usually little change in the number arriving whatever direction the telescope was pointed in and whatever time of day.

Part of the trouble, as we now know, is that most of the cosmic rays clicking ground level detectors are generated in the upper atmosphere from the 'real', primary, cosmic rays. These are raw star stuff, highly energetic charged particles coming mainly from very energetic stellar processes such as supernova explosions. Some come from the corona of the Sun. Amazingly enough, the cosmic ray window lets us sample material from other stars without going there. It is quite an extraordinary discovery. Unfortunately pointing a cosmic ray telescope in a given direction doesn't point to the source. The trajectory of a charged particle is bent into a spiral by a magnetic field and all cosmic rays from other stars must pass at least through the interplanetary magnetic field generated by the Sun before reaching us. This almost randomises the direction they reach us, making it hard to pinpoint the source.



Generation of secondary cosmic rays. Image by Helmholtz Alliance for Astroparticle Physics

One field of modern cosmic ray studies is investigating rare but almost unbelievably energetic cosmic rays. Our most powerful particle accelerators such as CERN's Large Hadron Collider create particles with an energy of just under 10^{13} electron volts. Some cosmic rays have been found to have energies ten million times greater, at 10^{20} electron volts and higher. The Pierre Auger observatory in Western Argentina covering 3000 km^2 is one of a number of observatories especially built to look for 'ultra-high energy' cosmic rays. How were they created? Not by any Earth-based technology we can imagine. They are too high energy to be deflected significantly by the interplanetary magnetic field but they are deflected by the galactic magnetic field. Making some allowance for this, their source appears to be beyond the Milky Way. Cosmic rays are indeed a window onto the most energetic processes in the Universe.

Radio astronomy

Karl Jansky was the first to detect galactic radio waves and realise what they were when he was working for Bell Labs in 1932. He didn't win a Nobel Prize. Penzias and Wilson were the first to detect the cosmic microwave background in 1964 while working for Bell Labs. They were awarded a share of the Nobel Prize in 1978. Martin Ryle and Anthony Hewish won the Nobel Prize in 1974, Ryle for developing the 'aperture synthesis' technique that can produce outstanding resolution and Hewish for the discovery of pulsars. Hulse and Taylor won the Nobel Prize in 1993 for their work with pulsars confirming Einstein's prediction of gravitational waves; Mather and Smoot received the Nobel Prize in 2006 for their work in measuring and interpreting the anisotropy of the microwave background. These prizes suggest quite rightly the power of radio astronomy to tell us about the Universe at large.

A hundred-metre diameter steerable radio telescope dish rising above the surrounding landscape is a truly impressive sight. Through its detection of the 21-cm radio emission from neutral hydrogen atoms, the distribution of hydrogen is mapped in the Milky Way. Indeed, the motion of the hydrogen around the galactic centre can be determined from the Doppler shift of this emission. The detail that can be seen is determined by the number of wavelengths across the diameter of the dish, which is just under 500. This is much, much less than even the smallest telescope achieves at optical wavelengths. The development of Ryle's synthetic aperture technique allows signals from antennae even hundreds of kilometres apart to be combined as if they were coming from one gigantic dish. The resolution of radio telescope 'images' from arrays can be now as good as that from optical telescopes, if not generally better. It was also Ryle who showed that distant galaxies seen earlier in the evolution of the visible universe were closer together than galaxies typically are now, providing hard to refute evidence for the expanding universe.

The Lovell radio telescope courtesy Mike Peel; Jodrell Bank Centre for Astrophysics, University of Manchester.

Large arrays such as ALMA in Chile, LOFAR in Europe, and the up-coming SKA in southern Africa and Australia, to name three, allow a huge range of mapping options for specific molecules and radicals in supernovae remnants, star-forming nebulae and galaxies. It was Ryle who showed that distant galaxies seen earlier in the evolution of the visible universe were closer together than galaxies typically are now, providing hard to refute evidence for the expanding universe.

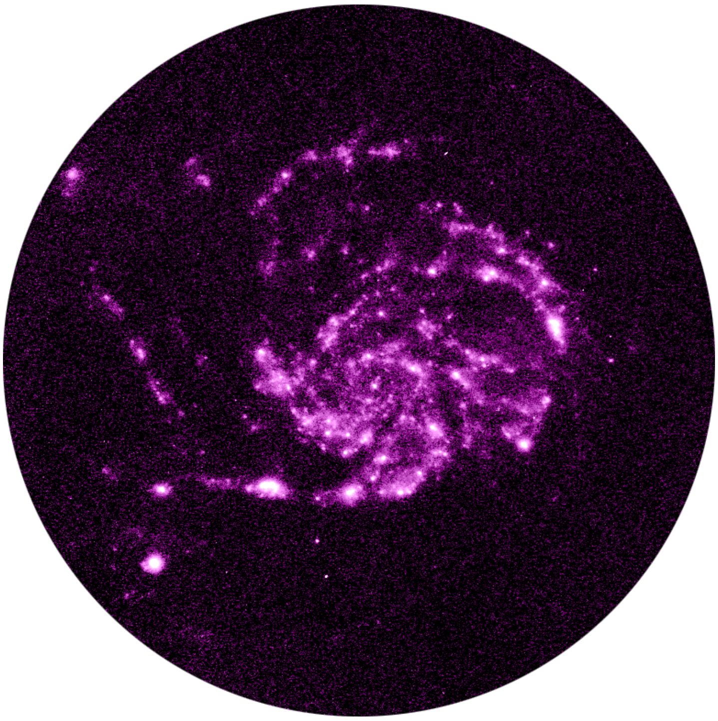
About half of the Alma Observatory radio array in the Atacama Desert at 5 km altitude. Image M. Struik (CERN)/ALMA (ESO/NAOJ/NRAO)

Radio astronomy has been an important tool for discovering galaxies with very active nuclei emitting high energy jets of particles that stream out for thousands of light years. The emission from the centre of these galaxies is considered to be powered by matter infalling to a 'supermassive' black hole that generates more radiation than all the stars in the galaxy. This type of galaxy includes quasars, blazars and a range of 'exotic' behaviour largely absent from our local group of galaxies. Active galactic nuclei and their jets emit over much of the electromagnetic spectrum but they may be accompanied by huge lobes of gas that are particularly powerful emitters at radio wavelengths. Through these and other discoveries, radio astronomy has considerably widened out view of what is in the Universe.

UV and infrared

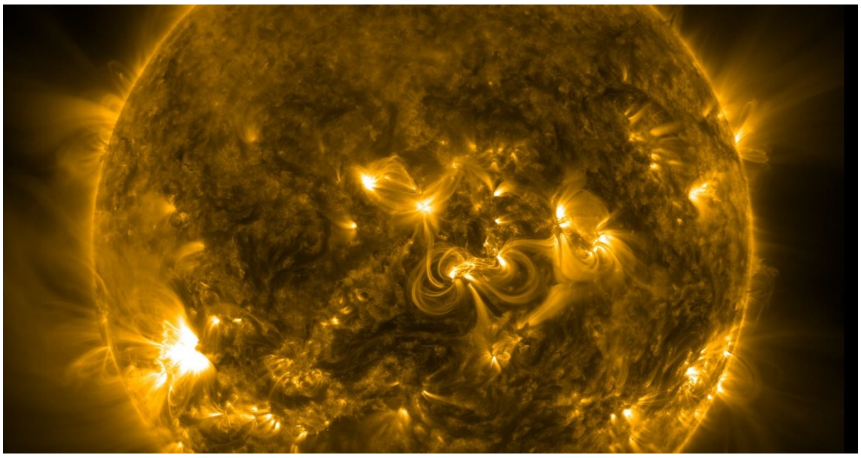
Both ultraviolet (UV) and infrared (IR) were discovered in sunlight early in the 19th century but they were not seen as part of a spectrum of radiation. It wasn't until the mid-1860s that James Clerk Maxwell deduced the existence of electromagnetic waves and immediately recognised light and radiant heat as electromagnetic. Infrared came to be called 'dark light' by contemporaries. UV is equally invisible to us but it was still decades before the 'electromagnetic spectrum' would become a familiar concept.

Fortunately for us, UV is mainly absorbed by the atmosphere. The UV that isn't absorbed is strongly scattered so looking though the atmosphere in UV is like looking through frosted glass. UV astronomy had to wait for the space age. Stars hotter than 8000 degrees emit the peak of their radiation in the UV. UV images of galaxies pick out the high-mass, fast-burning hot stars, highlighting the location of relatively recent star formation. In order for us to see anything, images have to be rendered in false colour. Blue or purple is a common choice.



The spiral 'pinwheel' galaxy (M101), 21 million light years distant, imaged in UV. Courtesy NASA.

The Sun has been imaged in UV continuously for decades now. Different false colours are used for different wavelengths, selected by filters. These are typically centred on the emissions of highly ionized iron atoms. The result is to select regions in the Sun with different degrees of energetic activity, showing that the Sun has a far more varied appearance than it seems to in visible light. The features both rotate with the Sun and develop or fade as they evolve. Most activity is associated with the very variable magnetic field that bursts out from the Sun's surface.



Solar Dynamics Observatory image taken in extreme ultraviolet at 30.4 nm wavelength of the Sun in a very active phase. Courtesy NASA/SDO.

In hindsight, infrared astronomy could have been developed much further in the 19th century but in fact it has largely evolved since mid-20th century. 'Near infrared' can use variants of optical technology but 'far infrared' extends into the realm of THz radio technology. The atmosphere has regions of absorption and transparency to IR but it also emits its own IR by virtue of its temperature, so high altitudes or space are the appropriate places for IR telescopes.

Infrared astronomy is the flavour of the times as I'm writing, so much so that the successor to the Hubble Space Telescope (which includes a dozen separate instruments spanning the near IR, visible and UV) will be an infrared instrument. Infrared shows up the radiation from astronomically cool objects. This includes huge gas clouds from which stars are born, stars much cooler than our Sun (of which there are many) and even planets. In the infrared, hot stars outshine cool bodies by far less than they do in visible light. Very distant bodies in the universe, and hence bodies created in the early universe, have their light red-shifted into the infrared. Infrared astronomy is an essential tool for studying the early universe and hence fleshing out detail on the creation story of the universe as we see it.

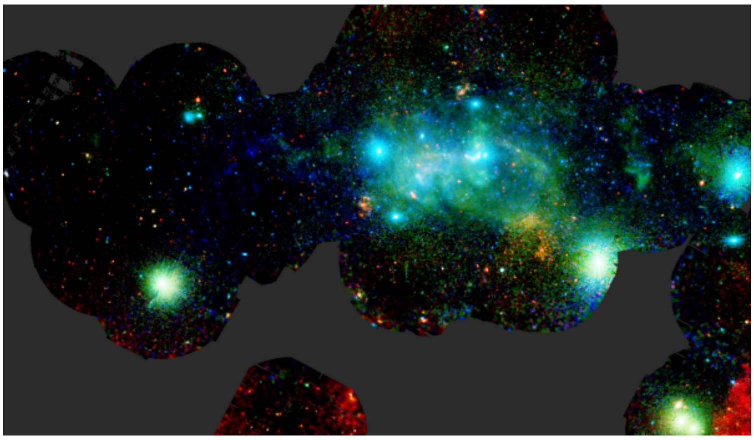
The famous 'pillars of creation' seen by the Hubble Space Telescope in infrared, revealing stars forming within the pillars and beyond them. Courtesy NASA.

X-rays & gamma rays

X-rays were famously discovered by Röntgen in 1895 and they are not absorbed much by air in a room. The depth of the atmosphere, though, is a different proposition. Above each square metre of surface on the ground there is about 10 tonnes of atmosphere, at least at sea level. X-rays have no hope of penetrating that thickness of material so X-ray astronomy seemed to be a non-starter. Indeed why bother to look, for a body as hot as the Sun should emit a negligible fraction of its radiation as X-rays. The first X-ray telescopes launched into space increased our view of the universe. The Sun does indeed emit at X-ray wavelengths, powerfully enough to be imaged. The X-rays come not from the hot photosphere we see with our eyes but from the exceedingly energetic corona that surrounds the Sun. X-rays are found to be emitted around the universe. Some sources are: hot gas (many millions of degrees) between galactic clusters, colliding galaxies and supernova remnants. X-ray flares have been seen coming from the centre of our galaxy and from close binary systems. X-rays are produced by rapidly accelerating (or decelerating) very energetic charged particles, including electrons and ions. Sources of X-rays in the universe are therefore places at extremely high temperature. The Chandra Source Catalogue release 2.0 of 2018 contains over 300,000 astrophysical X-ray sources. Any source detected by a small instrument in Earth orbit is producing a vast X-ray emission.

Gamma (γ) ray astronomy records photons at even greater energies than X-rays. The more energetic gamma rays (GeV) can reach ground-based observatories such as MAGIC on the island of La Palma or HESS in Namibia. Space craft will capture less energetic gamma rays and recent craft at the time of writing have been ESA's INTEGRAL, the international Fermi Gamma-ray Space Telescope and NASA's Swift telescope especially aimed at locating fast gamma ray bursts. Gamma ray bursts have been intriguing astronomers for decades. These intense bursts may last for only a hundred seconds or so. Years of detective work have located many of them to billions of light years away (and hence much earlier in the history of the universe). The intensity of the sources must be truly astronomical to produce readily detectable bursts at this distance away, the violent universe revealed. Other sources of gamma rays, and about 2000 have been identified, are often those energetic locations that also produce X-rays.

One of two MAGIC gamma ray telescopes at the Astronomical Observatory of El Roque de Los Muchachos on the island of La Palma. Photo Nik Szymanek.



Looking towards the centre of our galaxy with X-ray vision. Image taken with the ESA's XMM-Newton satellite (G. Ponti et al., 2015)

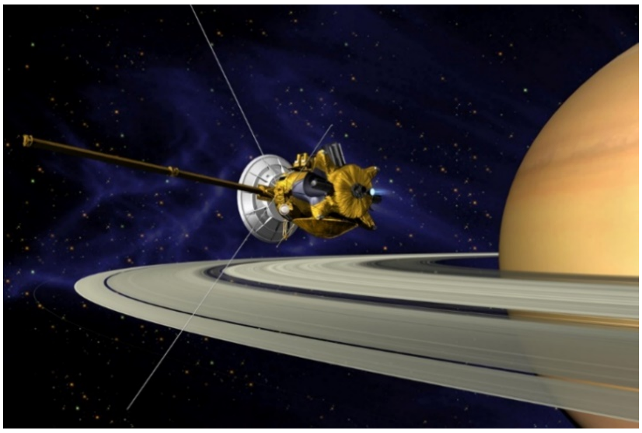
Satellites & space probes

As I'm writing this piece, the sixtieth anniversary of the launch of Sputnik-1, the first artificial satellite, has come and gone. Sputnik-1 contained no scientific instruments but having proved that the technology of inter-continental ballistic missiles could launch satellites, then instruments were not long in following. The main point of astronomical satellites is to observe above the atmosphere. The atmosphere absorbs radiation, distorts radiation and adds its own contribution. This is true for almost all of the electromagnetic spectrum and for cosmic ray detection. [The international space station (ISS) is more concerned with the technology of surviving in space and 'zero g' experiments, experiments in free-fall that simulates no gravity]. Rockets and balloons were used before satellites to get partial and temporary relief from the atmosphere. Some of what satellites have done for astronomy can be inferred from other sections of this piece. Since there are over 1500 active satellites in orbit, and thousands more no longer active, no summary is offered here. Most of the 1500 are Earth observation satellites (civil and military), communications satellites and GPS satellites. Perhaps the Hubble Space Telescope is the most famous of all the astronomical satellites.

Hubble Space Telescope in orbit. Courtesy NASA.

Space probes are mainly about getting up close to the rest of the solar system. They have been in the news since Pioneer 5 was launched in 1960 to investigate the radiation and magnetic field found in interplanetary space between us and Venus. The other use of space is to conduct experiments that can't be done on Earth. One such satellite experiment was Gravity Probe B, testing predictions of Einstein's theory of General Relativity (they were vindicated). A space probe with a related mission is LISA Pathfinder, aimed at testing the technology to detect a greater range of gravitational waves than can be done on Earth.

Apart from reporting in detail on interplanetary space since the 1960s, space probes have orbited all the planets from Mercury to Saturn, hugely widening our knowledge of the solar system. Mercury can't be seen in detail from Earth since it is small, a long way away when farthest from the Sun in the sky and its appearance still affected by twilight or pre-dawn light. It has now been mapped in detail [See the US Geological Survey YouTube video for its overall topography], its internal structure deduced from a gravimetric analysis and its thin atmosphere characterised. Completely cloud-covered Venus has had its surface revealed by radar and its astonishing surface conditions imaged by Russian Venera landers. The Moon has of course been visited on 6 occasions by astronauts but has also been the subject of millions of images and some remote landers and impactors. Mars has been under close scrutiny since the first Mariner probe flew past in 1964.



The Cassini probe beside images taken by Cassini of Saturn and Saturn's rings. Courtesy NASA.

The atmospheres of the 'gas giants' Jupiter and Saturn have been explored over years and their huge retinue of accompanying moons has been expanded and found in some cases to be possible harbingers of life in the solar system, far further from the Sun than life had previously been thought possible. The remaining outer solar system of planets have all been seen in flyby. Dwarf planets Pluto and Ceres showed only a few blurry features in Earth-based instruments prior to space probe images revealing fine detail of their surfaces. The first detailed picture of an asteroid was made as recently as the 1990s. Space-probes have followed comets, impacted them and even landed. Other probes have concentrated on the Sun, the most important solar system object of all for life on Earth. Yet more probes have followed Pioneer 5 in exploring the composition of the solar wind and the details of the interplanetary magnetic field. Data has been collected by the two Voyager spacecraft launched in 1980 and 1981 that are still transmitting from just beyond what is often seen as the boundary of the solar system.

Our picture of the solar system has changed utterly from that available in mid-twentieth century, revealing it as an amazingly varied, dynamic environment in which we live on one remarkable planet.

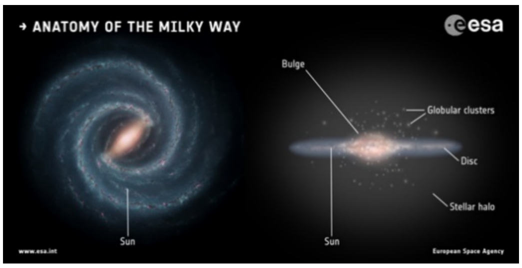
Astrometry

Astrometry is the measurement of stellar location and movement. Measuring position and speed sounds like pretty rock-bottom physics. Surely it can't get less glamorous than this - a bit like botanists mapping the location of plants or birdwatchers mapping habitats of species? I suspect that naturalists would say that such activities can be mundane but when you look at the whole picture they underpin the hugely important study of ecology. Astrometry is vital, too, for creating the picture of the universe at large and understanding why what we see is where it is now. Astrometry also turns out to be a lot harder and more sophisticated than recording flowers.

Star charts show only the position of stars in the sky. Just two coordinates will locate a star. Position in space needs three coordinates, distance away being missing in star charts. Motion needs another three parameters for speed: left/right, up/down, towards/away. So, star charts capture just two of six numbers that are at the base of astrometry. If we had all six for everything we can see, we would get the structure of the universe at large and how everything is changing. That's an aspiration we'll not achieve. One problem is that the universe is stupendously large and even the distance to the nearest star is colossal. Stars may be moving at hundreds of km per second but no motion can be seen from day to day. They were called 'the fixed stars' for good reason. As we now know, no stars are fixed. The universe is a dynamic, changing place but it's necessary to focus on the right distance and time scales. That's where astrometry comes in.

While still on fundamentals, I should say that the basis of distance measurement in science is the metre; the basis of speed measurement is the metre and the second. The astrometry I want to introduce here is measurement of position and changes that can be taken back directly to the metre and the second. There are means of estimating distance from spectroscopy and photometry that indirectly give results. These are mentioned elsewhere.

People have been recording star positions for millennia, probably since the idea of making records was conceived. However, I'd date the beginnings of astrometry in the service of astronomy to the 19th century. The seafaring nations of the world encouraged astronomers to measure stellar positions accurately as a means of improving the accuracy of navigation.



Our galaxy, as deduced with the aid of astrometry. Courtesy ESA.

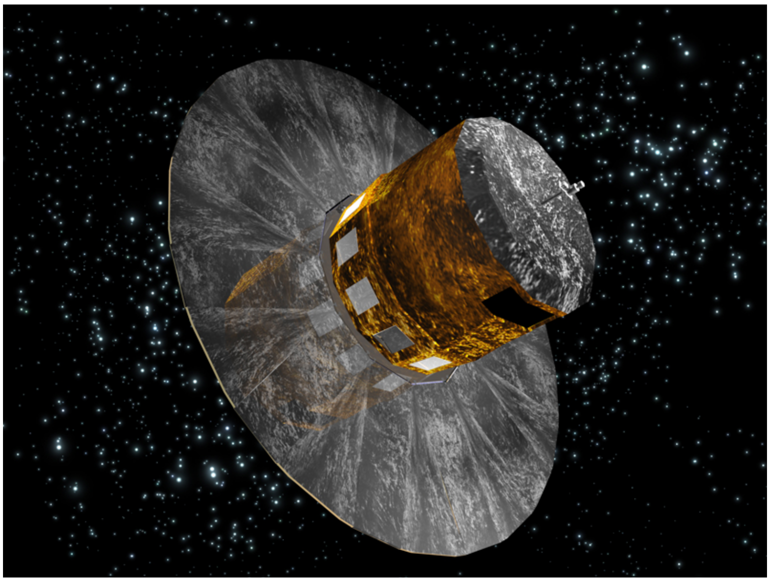
Astronomers and their instrument makers developed equipment that could do much better than the precision needed for navigation. They had worked out that nearby stars would appear to move relative to distant stars over a time of six months, the time it took the Earth to move its position in space to the other side of its orbit. The effect is an example of parallax. Just how big is stellar parallax?

Stellar parallax is in fact too small to have been observed in the 18th century and earlier. The first person to succeed in finding a fairly reliable value was Friedrich Bessel in the 1830s. His answer was about three-quarters of a second of arc for the apparent motion of the star 61 Cygni over 6 months. The technique expands the distance scale from metre, to size of the Earth, to orbit of the Earth, to star. That is the basis of astrometry. In fact astronomical distances are often given in terms of parallax, the basic length being the radius of the Earth's orbit, not its diameter. 1 parsec is the distance that produces a parallax of 1 second of arc. It's actually too small a distance for any star. 100 parsecs is 100 times this distance, producing a parallax of 1/100th of a second of arc. One degree is quite a small angle and there are 3600 seconds in a degree, so measuring parallax requires the highest precision instruments.

By early 20th century there were still only a handful of observatories that could carry out astrometry and had observers with adequate skill and patience. By then only a modest number of stars had their distance measured using parallax. However, stellar motion also produces a change in the position of stars and the same accuracy of observation was sufficient to detect local motion over a time of no more than a few years. Importantly, this was motion across the field of view. Stellar motion is somewhat of a contrast to detecting position. Motion towards/away is quite easily detected by the corresponding blue shift/red shift of spectral lines. Motion across the field of view is measured by tiny changes in angle. In early 20th century the motion of some nearby stars was measured and the general rotation of the Milky Way around the galactic centre hinted at.

In fact, located at the bottom of the atmosphere, one can't really do much better in terms of accuracy than was done then. Over decades the distance scale was extended outwards, largely using photometry. Far distances remained pretty uncertain.

The next big advance in astrometry needed a jump into space, which was done with ESA's Hipparcos satellite in the early 1990s. The parallaxes and the motion of over 100,000 stars were measured to about 2 milliarcseconds. About four times that number of stars were measured to lower accuracy but very considerably better than any previous knowledge.



Not a Hogwarts magical hat but something real and even better: the Gaia probe against a backdrop of stars.

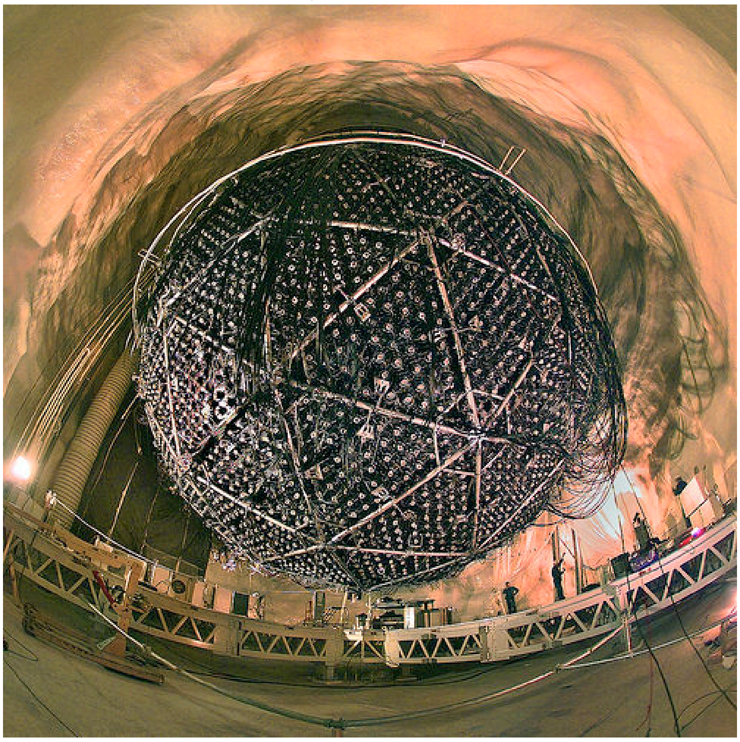
Mankind now had a good idea of our stellar surroundings in three dimensions out to about 1000 light years away. Hipparcos was good. It revised our near distance scale and hence the accuracy of further distances. ESA's Gaia probe is taking astrometry to a new frontier. Gaia is situated 1.5 million km from Earth, orbiting the Sun once a year looking away from the Sun. As I'm writing it is still making basic astrometric measurements (and photometric and spectroscopic measurements) on about one billion stars to an accuracy about 200 times that achieved by Hipparcos. Through Gaia we shall really know our galactic surroundings and how they are changing. We shall be able to deduce how our galaxy has picked up and assimilated other smaller galaxies, identify stars that are not participating in the general rotation of the galaxy, find the distinctive features that separate the galactic halo from the disk, and much more. Astrometry, being built on the foundation of the metre and second, is providing bedrock knowledge of our galaxy that will inform mankind indefinitely into the future.

Neutrinos

The idea of a neutrino was originated by Wolfgang Pauli in 1930 and the name coined by Enrico Fermi a couple of years later. It was conceived as a particle with no charge and probably zero rest mass that would carry away energy in radioactive beta decay. When particle physics came of age later in the century it was realised that neutrinos fitted very naturally into the bigger scheme of things. There were neutrinos and anti-neutrinos; three different kinds corresponding to three variants of beta decay. Once created, though, they hardly interact with matter at all. The Earth itself is almost completely transparent to neutrinos. What has made detection possible is the vast number produced in the underlying process of nuclear fusion that powers the Sun and the processes of nuclear fission and decay that take place in reactors. Given neutrinos in vast numbers, a few will be detected.

Frederick Reines was awarded a share of the 1995 Nobel Prize in Physics "for the detection of the neutrino".

Neutrino astronomy means chasing rare events – the capture of a neutrino by an atom followed by its distinctive transmutation that ends with a characteristic pulse of radiation being emitted. It is the radiation that is detected. Neutrinos are produced by all stars in their normal fuel-using capacity; there is a residual cosmological background of neutrinos (not experimentally detected) originating from the 'big bang' and neutrinos are produced in violent events such as supernovae explosions.



The detecting array at the Sudbury Neutrino Observatory more than 2 km below ground. Note the size of the person in the gallery. Arthur McDonald working here shared the 2015 Nobel Prize in Physics "for the discovery of neutrino oscillations, which shows that neutrinos have mass".

Neutrino 'telescopes' are typically located deep underground, or underwater, or in Antarctica under the ice, to shield them from detecting cosmic ray induced events. Their first extremely useful function was to confirm (eventually) that the standard model describing how the Sun produced its energy correctly predicts the number of solar neutrinos observed. Neutrino astronomy aiming to provide more information on extreme events in the universe is a developing arena in the 21st century. Because of the rarity of neutrino detection, it will be a subject that develops slowly.

Gravitational waves

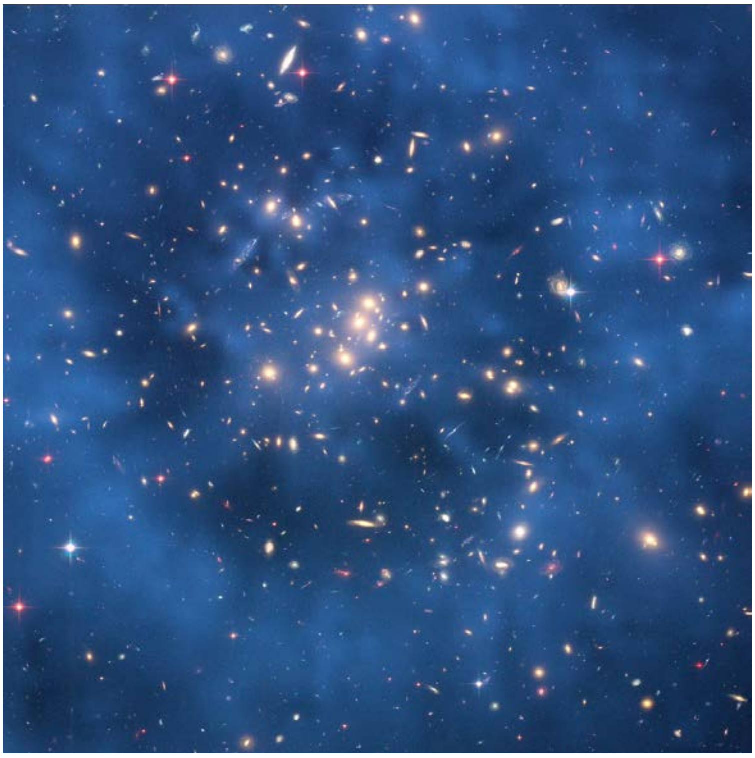
Since the 1960s, astronomers have been trying to detect gravitational waves. The 1993 Nobel Prize was awarded to Hulse and Taylor for their detection and analysis in the 1970s of the signals from a pulsar orbiting another neutron star. The rate of change of the signals over a long period matched that expected if gravitational waves were given off as their binary orbits drew closer together. Not the detection of gravitational waves but strong evidence for their generation in expected circumstances. Confirmed detection did not come until 2015, some half century after the early attempts. The announcement was made in February 2016. It was one of the astronomical events of the decade. I remember where I was on my bicycle when our younger son phoned me to tell me the news. As I pen this introduction, four gravitational wave events have been detected by the LIGO observatories and the instigators of LIGO have been awarded the Nobel Prize in Physics for 2017.

LIGO Livingston, half of the LIGO gravitational wave observatories. Courtesy LIGO Caltec.

The first four gravitational waves observed came from violent events, the merger of black holes. The signatures of the waves allowed details of the mergers to be deduced, such as the masses involved, their distance (over a billion light years for all four events) and information about the spin of the merging objects and the energy transformed into gravitational waves. The next wave detected, on August 2017, was from merging neutron stars of a few solar masses, a 'mere' 130 million light years away. This event was pinpointed sufficiently accurately in the sky that it could definitely be linked to an accompanying a gamma ray burst. That associated one of these previously mysterious bursts to a definite, well characterised event, thanks to the gravitational wave. Gravitational waves themselves are absolutely miniscule by the time they reach the Earth, making detection a tour-de-force. Other detectors of adequate sensitivity are coming on line and the 2015 event is indeed likely to be the first event seen through a new window on the universe, revealing that events of extreme violence occur comparatively frequently somewhere in the observable universe.

Dark matter

How can dark matter be a window on the universe? Surely it is invisible and it has never been detected after decades of trying in 'laboratories'? Is it not like trying to draw a picture of coal in a coal cellar without any light? Well yes, but a bat could make a good go at finding the distribution of coal in a coal cellar at the dead of night, for it uses another means, not light. So it is with dark matter. We need to 'observe' with a means other than electromagnetic radiation. Dark matter is not coal or any other dark object we can think of. Dark matter is mapped only through its gravitational influence. Our galaxy, the Milky Way, is deduced to be surrounded by a near spherical halo of dark matter. Images of dark matter are necessarily the result of a computational deduction of how much dark matter must be present to create the observed gravitational effect.

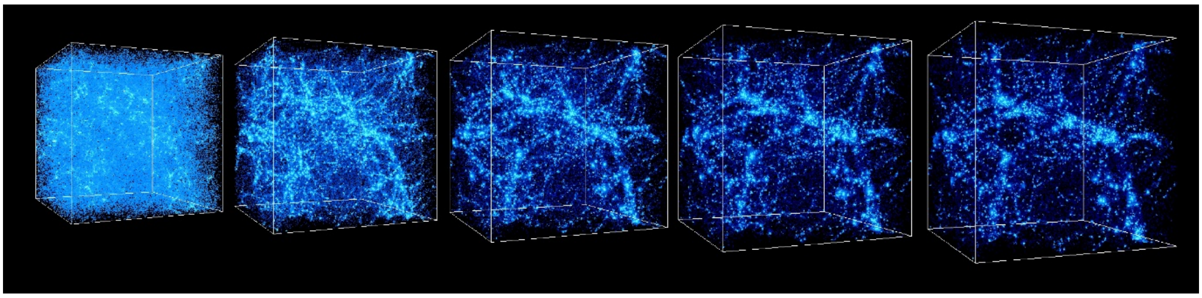


A cluster of galaxies (CL0024+17) seen by the Hubble space telescope showing multiple images of galaxies caused by an unseen ring of dark matter about 5 million light years across that has been superimposed in diffuse blue. Courtesy NASA.

The presence and distribution of distant dark matter can be deduced from its gravitational lensing effect on very distant galaxies. The total amount of dark matter present in galaxy clusters can also be deduced to agree within reasonable limits with the amount expected. Cosmology predicts that dark matter should amount to more than five times the amount of 'star stuff', the stuff of the periodic table. It is, of course, immensely frustrating that we can't detect it directly or have a clear idea of how it fits into all we know about elementary particles. In this sense, dark matter remains one of the great mysteries of the universe. Some astronomers even deny it exists but not only can its distribution be mapped in favourable circumstances but computer models of galaxy evolution don't work convincingly without dark matter included. Dark matter fits in with a range of different phenomena to the extent that I would be surprised if it were found to be a mistaken concept. It is part of our current understanding of the universe.

Computing

Surely I must be kidding to say that in staring at a computer screen we are looking into a window of astronomy? Even though almost every professional astronomer does it, that doesn't make it a window. It can be, though. Astronomy is a very peculiar science. By and large you can look but not touch. It's impossible to experiment on the universe at large. With a lot of effort, one can conduct simple experiments on a few nearby objects in the solar system but that's not even a drop in the ocean compared with the universe.

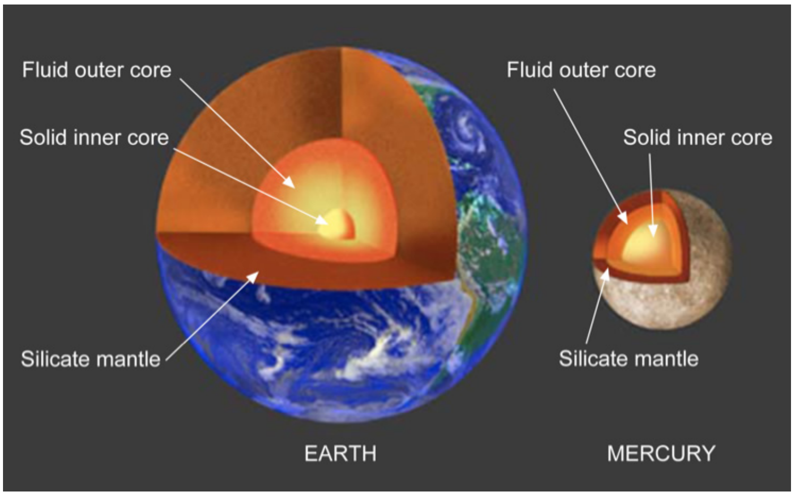


Example of modelling the evolution of the large-scale structure of the universe by the National Science Foundation Center for Computational Physics.

Computing allows us to undertake experiments, not on the universe itself but on our understanding of it. If that understanding is good, then the computation will mimic what we see through our windows. For example, can we model the evolution of clusters of galaxies? Does the model produce the kind of structures we find in the universe? If we vary the amount of dark matter in the model, do we get better or worse answers? Can we model the dynamic behaviour of the Sun's magnetic field in a way that produces realistic solar flares, or have we not yet understood the details of what is going on there? Do predictions of the evolution of the solar system over the past 4 billion years produce what we find is out there now? Can we understand the conditions that produce the very odd configurations found for a range of extra-solar planets? And so on. Not experiments on the universe but a window that truly increases our understanding of the universe.

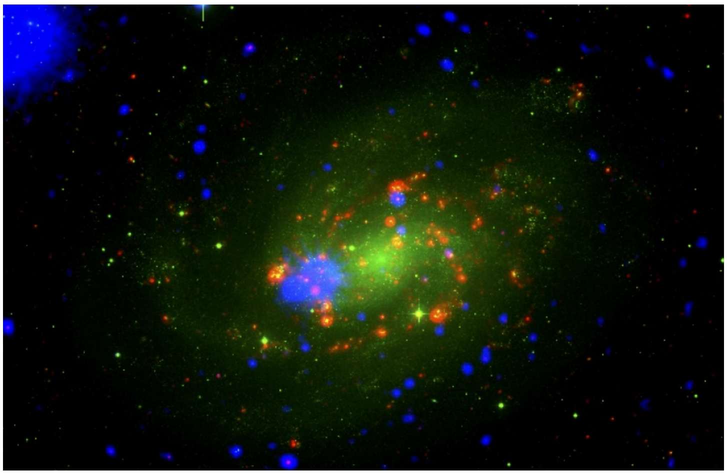
Computing has another role. It can allow us to work out what we can't see. Any astronomy book will show you cut-away diagrams of the interior of Mercury, Mars, Jupiter, other planets and some moons. How do we know? Computation allows us (well, at least specialists) to work out from variations in satellite orbits the distribution of mass in the body being orbited. Satellites have been launched for the sole purpose of mapping gravity fields. Computing allows us to infer from the detection of gravitational waves what was happening as two black holes orbiting each other came together to produce the original burst of waves as they merged.

Computing allows us to see how the periodic table of elements is built up in stars and what happens in their final supernova explosions. At least it will do so when we understand the process better. In a myriad of ways, computing gives us a view of what is in the universe that we shall never see for ourselves. Yes, it is a window of astronomy.



The inner structure of Earth and Mercury deduced from satellite orbit variations. Courtesy NASA.

Multispectral imaging



Multispectral image posted by ESA showing stellar evolution around the 'nearby' galaxy NGC 300.

I've hesitated to call this a new window but on reflection I think it deserves the accolade. Multispectral imaging involves creating single images derived from observations in different parts of the electromagnetic spectrum to reveal what one contribution can't show. We'll see a lot more multispectral images in the 2020s and beyond. The accompanying image released by ESA in 2019 is a nice example. Most of the radiation comes from the galaxy NGC 300, about 6 million light years away.

The blue are sources detected at X-ray wavelengths by ESA's XMM-Newton space observatory. They represent a variety of very energetic sources: stars near the end of their life that are nearly supernovae, supernova remnants, neutron stars, black holes. The large blue blob partly showing top left is from exceedingly hot gas in a cluster of galaxies some 2 billion light years away.

The green shows 'normal' stars in the galaxy, observed in visible light. The red shows cool gas observed in the infrared by NASA's Spitzer space telescope. This is where future stars will be born.

Taken together, the image gives an impression of the old, the current and the new in terms of stellar evolution. Not quite a timeline but hinting at one.

John S. Reid

Oct 2017/Feb 2019