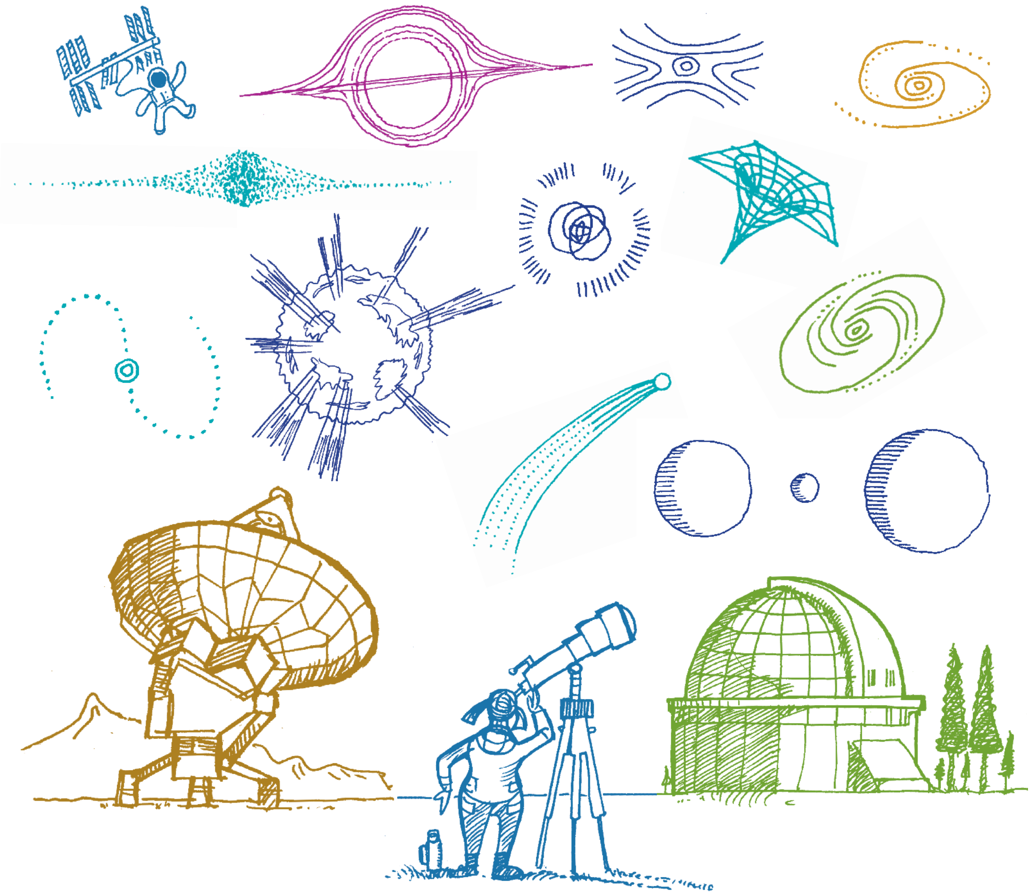
IOP Education | Stories from physics booklet 7

Astronomy and space

By Richard Brock



IOP Institute of Physics

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Introduction

This is the seventh book in our series. For many people, the wonders of the night sky are their first encounter with science. Seeing the Milky Way on a pitch-black night, identifying the moons of Jupiter through binoculars or looking at the wonderful images from the Hubble Space Telescope, astronomy inspires the imagination in a way that few other subjects can.

The history of astronomy is filled with fascinating people whose observations and insights have changed the ways we think. This subject may be at an immense scale, but at its heart is a human pursuit and the lives and experiences of these pioneers of astronomy add a rich texture to this subject.

The Scientific Revolution began with the work of an astronomer. In the 16th century, Copernicus changed our understanding of our place in the universe and modern science began. Today, astronomy and astrophysics are still at the cutting edge of science, developing innovative technologies and continuing to challenge our perception of the universe and where we sit within it.

We hope that this booklet will inspire others to look upwards and go further.

We would like to thank Richard for his work in collecting these stories and enabling us to share them with teachers.

Mark Whalley

IOP education manager

Message from the author

Perhaps of all the topics on the school physics curriculum, space most readily captures students' interest. The impossible-to-imagine numbers, cataclysmic events and strange conditions that exist in our universe have a compelling drama and majesty that makes them inherently engaging. There were many strong contenders for stories in this domain and it has been a challenge choosing just a handful for this booklet.

As usual, many stories are drawn from history. These include Schwarzschild's speedy solution of Einstein's field equations under the most challenging conditions, the French astronomer Le Gentil's troublesome expedition to observe the transit of Venus and Williamina Fleming, the Scottish maid who become a Harvard astronomer.

You will read about strange and wonderful objects - zombie stars, cannibal stars and the 'polystyrene' planet. You will discover the place where you can see the back of your head by looking forwards. Find out what the Milky Way smells of and where you might be able to find nuclear pasta. Discover Vulcan, the phantom planet that wasn't there.

We begin with stories that show the human side of astrophysicists. You will meet the first scientist, Mary Sommerville, and her culinary protest against the slave trade, read about the blind astronomer who has made astrophysics audible and share Jocelyn Bell Burnell's stoicism at missing out on a Nobel Prize.

I am grateful to the Institute of Physics for making this collection of the stories a reality. In particular, I want to thank Caroline Davis for managing the project and editing the booklets, Mark Whalley for his helpful comments on the text and Stuart Redfern for his wonderful illustrations.

So, let me tell you some stories about physics...

Richard Brock

Astonishing astronomers

No blue sky thinking!

Ernest Rutherford is reported to have disliked blue sky thinking in his laboratory. He is said to have remarked: "Don't let me catch anyone talking about the universe in my department!"

Somerville the first scientist

Mary Somerville was a remarkable polymath who published research on a number of scientific topics as well as writing popular science books. Born in 1780, from a young age, Somerville was determined to receive an education, writing:

> From my earliest years, my mind revolved against oppression and tyranny, and I resented the injustice of the world in denying all those privileges of education to my sex which were so lavishly bestowed on men.

She was also a principled young woman – Mary and her brother refused sugar in their tea in protest at the slave trade. Somerville worked on developing Laplace's mechanics to explain the deviation of planets' orbits from perfect ellipses and the complex motion of the Moon around the Earth. She noted the perturbations of Uranus' orbit and predicted the existence of Neptune. Her book, *On the Connexion of the Physical Science*, was amongst the best-selling science books of the 17^{th} century. In addition to her contributions to astrophysics, Somerville was perhaps the first person to be labelled a 'scientist', a term used by a reviewer of one of her books in 1834.

Hubble's trouble

Edwin Hubble was born in Missouri in 1889 and grew up near Chicago. A story reports that Hubble's high school principal approached him at his graduation and said, "Edwin Hubble, I have watched you for four years and I have never seen you study for ten minutes." The teacher is said to have paused and then continued, "Here is a scholarship to the University of Chicago." Some biographers have suggested that Hubble was a compulsive liar who made up stories of bravery and athletic prowess.

Nonetheless, the scientist has an impressive record of achievement and stories about him abound:

- Whilst at the University of Chicago, Hubble excelled as a boxer. A promoter was eager to set up a fight between the physicist and Jack Johnson, the then world champion, but Hubble declined the offer.
- During the First World War, Hubble served in the army and was knocked unconscious by the blast of an exploding shell whilst in an observation balloon. As a consequence of the explosion, he could never fully straighten his right elbow.
- Hubble was selected to be one of the first Rhodes Scholars and returned to America from Oxford with an affected British accent, which he is reported to have maintained for the rest of his life.
- Hubble was a competitive academic. Despite, or perhaps because of, his celebrity status, he is reported as showing an 'ungenerous' and 'vindictive' attitude towards colleagues. When his work on galactic classification was scooped by the Swede Knut Lundmark, he wrote to the scientist to express his feelings:

  > This is a very mild expression of my personal opinion of your conduct and unless you can explain in some unexpected manner, I shall take considerable pleasure in calling constant and emphatic attention, whenever occasion is given, to your curious idea of ethics.

  Hubble's response is somewhat hypocritical given that, in 1927 Lemaître (see page 16) published a version of what is now referred to as Hubble's law, pre-empting the American astronomer by two years but attracting little notice. It has been speculated that, when Lemaître's version of the recession law was translated into English for publication, Hubble, or someone sympathetic to him, deliberately mistranslated the paper to minimise Lemaître's claim to prior discovery. In 2018, the International Astronomical Union recommended that the law now be known as the Hubble–Lemaître law.

- Following his death, Hubble's wife did not want to hold a funeral for her husband and never revealed what happened to his body.

Le Gentil's journey

A strong candidate for the title of 'most unfortunate astronomer' is the extravagantly named Frenchman Guillaume Joseph Hyacinthe Jean Baptiste Le Gentil de la Galaisière. Le Gentil believed that Halley's calculations for the transit of Venus were inaccurate and he was sent by the French government to observe the 1761 transit in Pondicherry in India, then under French control.

However, three months into his voyage, whilst breaking his journey at Mauritius, Le Gentil learned that the Indian Ocean was under the control of the British Navy. Undeterred, he continued his journey only to discover, whilst off the Indian coast, that Pondicherry had fallen to the British. The transit occurred whilst he was returning to Mauritius and heavy seas and poor visibility interfered with his measurements.

Le Gentil chose to stay in Mauritius to study the islands and made plans to travel to Manila for the next transit in 1769. However, on arriving in Manila after three months at sea, he learned that the governor would not allow the establishment of an observatory. He again set sail for Pondicherry, which had since been re-established under French control. But having finally reached Pondicherry and set up his observatory, the day of the transit proved to be overcast.

Devastated, Le Gentil planned to leave by the next available ship but contracted a serious illness and did not leave till the following year. On his journey home, his ship was nearly sunk by a storm and he was forced to return to Mauritius where he boarded a returning Spanish warship and travelled over land from Spain. On his arrival in France, 11 years after setting out, he discovered that he had been declared dead, his estate divided up and his chair at the academy taken by another scientist.

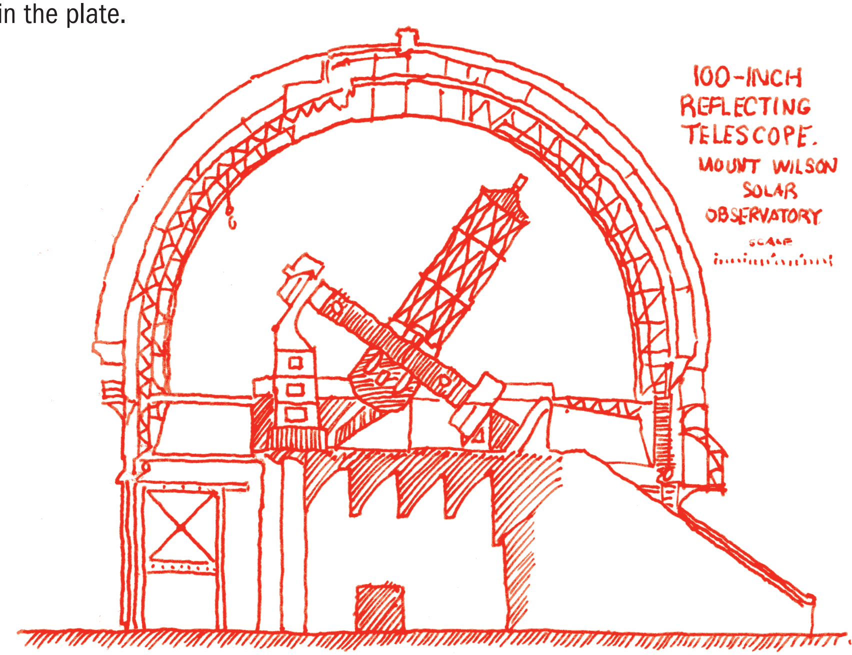
Nonetheless, his story has a happy ending: Le Gentil published the story of his adventures which became a financial success. He went on to marry a wealthy heiress and regained his academic chair.

From mule driver to the stars

The story of American astronomer Milton Humason's career is a remarkable example of success against the odds. Humason dropped out of high school and was hired as a mule driver to help with the building of the Mount Wilson Observatory. An interesting aside is that when the telescope at Mount Wilson was constructed in 1904, the 22-tonne mount of the instrument was designed to float on a container of mercury to allow smooth rotation.

Whilst working, Humason talked to construction workers about the project and was hired first as a janitor and then as a darkroom assistant at the new observatory. He persuaded some of the astronomers to teach him mathematics and he was eventually appointed to the professional staff. Humason worked closely with Hubble and was awarded an honorary doctoral degree.

Although the discovery of Pluto is attributed to Clyde Tombaugh, Humason almost beat him to it. He had been directed to photograph certain areas of the sky and two plates he produced include images of the planet. However, in one, Pluto is too close to a star to be visible and in the other, the image of the planet fell on a flaw in the plate.



Beating the professionals

Grote Reber ranks among the many amateurs who have made significant discoveries in astronomy. He was a professional radio engineer and a radio ham who built the world's first dish-shaped telescope. Reber had wanted to work with the astronomer Karl Jansky, but when he applied to work with him at the Bell Laboratories during the Great Depression, there were no available posts. Undeterred, Reber built a radio telescope in his back yard with a 9 m metal dish. To save for the parts for his telescope, he chose not to buy a car but travelled on public transport.

Reber initially tried to detect emissions at the 3,300 MHz frequency because he believed that the radiation from the Milky Way would be from thermal sources. However, after finding no signal, he tried at 1000 MHz, again with no luck, before finally detecting a signal at 160 MHz. He carried out a careful mapping of the 'cosmic static' to develop the first radio map of the sky, avoiding interference from car ignition static by working at night, keeping his day job and only sleeping for a few hours after dinner.

When his contour map of static was submitted to an astrophysical journal, the editor was sceptical of the amateur's findings and sent two researchers to examine Reber's telescope. Once the results were determined to be credible, his map was published in 1944 and still coheres well with contemporary data.

Alpher, Bethe and Gamow

In order to explain the apparent overabundance of helium in the universe, George Gamow proposed the hypothesis that most of the helium in the universe today was produced in the early Big Bang in 'less time than it takes to cook a goose'. Gamow developed the idea that, after the Big Bang, the universe consisted of a soup of hot particles, which he referred to as *ylem*, a Greek word for the formless substance from which elements formed. He set a doctoral student, Ralph Alpher, the task of working out the reactions that led to the formation of heavier elements from the ylem. Gamow and Alpher developed their ideas into a paper titled *The Origin of the Chemical Elements.*

Gamow could not resist adding the name of his colleague, Hans Bethe, to the authors' list, even though he had made no contribution to the paper, in order that the names of the authors would sound like the first three letters of the Greek alphabet: Alpher, Bethe, Gamow.

The Herschels' astronomical journey

Brother and sister Frederick William Herschel and Caroline Lucretia Herschel collaborated on astronomical research in the 1700s and 1800s. William had intended to follow in his father's footsteps and pursue a musical career. As a boy, William played the oboe in a military band but life in the army held no appeal and he left Germany and settled in Bath to work as an organist. His musical career flourished and his public performances to the wealthy town society allowed him to earn more from music than the income of the Astronomer Royal at the time.

Becoming interested in astronomy

William invited Caroline, who was 12 years his junior, to live in Bath to escape her controlling mother and a life of domestic drudgery and to pursue her ambition of becoming a soprano. Whilst initially pursuing his musical career by day, William developed an interest in astronomy at night and both siblings were soon caught up in the astronomical obsession. Caroline reported that she was "much hindered in my [musical] practice by my help being continually wanted in the execution of the various astronomical contrivances".

Finding that writing notes harmed the dark adaptation of his vision necessary for observing dim nebulae, William asked Caroline to assist his note-taking. As his observations grew more ambitious, the mirrors available from local grinders were no longer suitable for William's research, and the siblings set up a foundry in the basement of their home, with Caroline spending hours making horse dung moulds for their mirrors. To add to the family industry, their brother Alexander also contributed to the constructions of telescope parts. The astronomical work for her brother impacted Caroline's musical ambitions and, when she was invited to appear as a soloist at a concert in Birmingham, she refused the invitation explaining: "I never intended to sing anywhere but where my Brother was the Conductor".

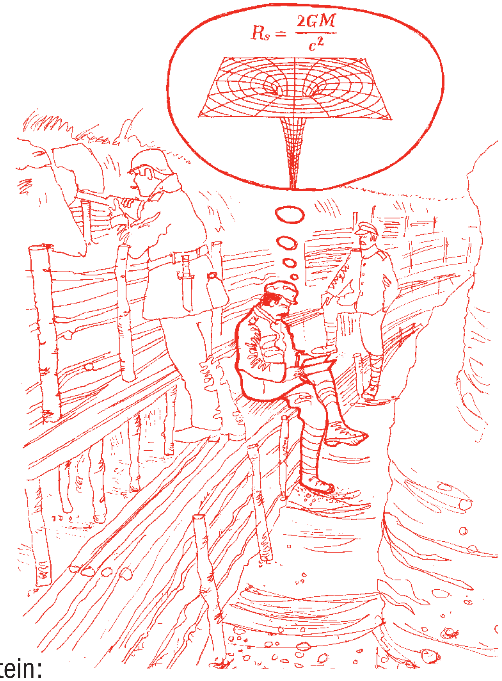
The first woman to be paid for science

William's discovery, in 1781, of what he initially thought was a comet but was later identified as a new planet, Uranus, led to academic recognition and a salary from King George III. William encouraged Caroline to sweep the sky for further comets but her observation of a number of previously unrecorded nebulae sparked her brother's interest in cataloguing the objects. By 1787, Caroline had claimed the discovery of 17 nebulae and, during her observing career, identified eight novel comets. She was granted an annual salary of £50 by the king and is claimed to be the first woman to receive a salary for scientific work. Caroline was awarded the Astronomical Society's gold medal and her citation noted that her work "may be considered as the completion of a series of exertions probably unparalleled either in magnitude or importance in the annals of astronomical labour".

Schwarzschild's war

The German physicist Karl Schwarzschild provided the first solution of Einstein's field equations, contributing to the understanding of black holes. Notably, he achieved the result only a few months after Einstein published his theory. More remarkable still, Schwarzschild carried out the work whilst serving in the German Army on the Eastern Front in 1916.

After obtaining his doctorate, Schwarzschild worked first with Hilbert and Minkowski before taking up a post at the German Astrophysical Observatory near Berlin. When the First World War broke out, though he was over 40, patriotism inspired Schwarzschild to join the army and he served in the artillery. Despite freezing conditions and when the fighting allowed it, he would catch up on his scientific correspondence.



In December 1915, a month after its publication, he received a copy of Einstein's paper on general relativity. It had been generally assumed that the nonlinear field equations in the paper would be challenging to solve. Remarkably under any conditions, but particularly so given the conditions on the front, within a month of publication, Einstein received a letter from Schwarzschild setting out a simple solution to the field equations. Einstein forwarded the letter to the Berlin Academy and it was published in January 1916. Schwarzschild wrote in a letter to Einstein:

> The war treated me kind enough, in spite of the heavy gunfire, to allow me to get away from it all and take this walk in the land of your ideas.

Unfortunately, Schwarzschild developed an incurable skin disease and died in 1916, only two months after returning from the front.

The woman who knew what stars were made of

In 2008, the IOP introduced the Cecilia Payne-Gaposchkin Medal and Prize for distinguished contributions to plasma, solar or space physics. The medal is named in honour of the brilliant but marginalised astronomer who discovered that stars are formed largely of hydrogen and helium.

Payne-Gaposchkin showed an early aptitude for experimental science, carrying out a controlled trial on the impact of prayer on her exam results at Sunday school: she reported that she obtained better results in exams when she had not prayed for success.

As a child, she was also a talented musician and was encouraged by her school music teacher, Gustav Holst, composer of *The Planets Suite*, to pursue a musical career.

Fortunately for the development of astrophysics, Payne-Gaposchkin chose to study science at Cambridge University. Whilst there, she reported the impact of getting one of only four tickets to attend a lecture by Eddington on his expedition to test Einstein's theory of relativity:

> The result was a complete transformation of my world picture… When I returned to my room I found that I could write down the lecture word for word (as I was to do for another lecture a couple of years later). For three nights, I think, I did not sleep. My world had been so shaken that I experienced something very like a nervous breakdown.

Payne-Gaposchkin moved to the United States and undertook research for a PhD on the spectra of stars. At the time, it was believed stars were composed of a similar mix of elements to the Earth, but her research showed this belief was mistaken, instead showing that hydrogen and helium were the most abundant constituent elements.

After reading her thesis, the eminent but orthodox astronomer Henry Norris Russell (of the eponymous diagram) encouraged Payne-Gaposchkin to drop her conclusion. In 1925, Payne-Gaposchkin published her ground-breaking finding in her thesis, down-playing it by writing: "The enormous abundances derived for those elements in the stellar atmosphere are almost certainly not real."

Decades later, Russell reached the same conclusions as Payne- Gaposchkin and acknowledged her work. Her thesis has since been described as "the most brilliant PhD thesis ever written in astronomy".

Pickering's female stars

The astronomer Edward C Pickering was director of the Harvard College Observatory for 43 years from 1877. He made significant contributions to astronomical photography and categorisation. However, what is most remarkable is that his team of researchers included an impressive array of women, exceptional for that time. However, whilst Pickering was progressive in encouraging women to contribute to research, the female members of his team were typically paid half the salary of their male colleagues.

Fleming's fantastic findings

One of the most well-known images of a nebula - the horsehead nebula - was captured on a photographic plate in 1888 by Williamina Fleming at Harvard Observatory. Fleming's story is remarkable: after immigrating to the United States from Scotland, she became pregnant only to be deserted by her husband. She came to work for Pickering, at first as a maid. One day, Pickering became so annoyed with the slow progress achieved by his male assistants that he stormed out of the building in a huff claiming that his Scottish maid could do a better job. This story may have been embellished in the retelling but, nevertheless, Fleming began to work with Pickering and went on to publish papers in prestigious astrophysical journals. She became an honorary member of the Royal Society which did not allow women as regular members at the time. Among Fleming's many achievements are the discovery of ten novae, over 300 variable stars and the first recorded spectrum of a meteor.

Jump Cannon's classification

One of the earliest systems of star categorisation, the Harvard system, was developed by Pickering and his team in 1890. One member of the group, Annie Jump Cannon, was a remarkable astrophysicist. As a child, she would conduct observations with her mother from an impromptu observatory built in the attic of the family home. During her youth, perhaps due to a bout of scarlet fever, Jump Cannon suffered severe hearing loss. Encouraged by her parents to study physics at Wellesley College, Jump Cannon did not pursue her interest in astronomy for ten years after her graduation. Biographers have suggested that the death of her

mother acted as the spur to restart her scientific career and she found a post at the Harvard College Observatory. Whilst working for Pickering, she developed an extraordinary ability to classify stars, being able to categorise the spectra of three stars per minute. She increased the star card catalogue from 14,000 entries to some 250,000.

Jump Cannon developed Pickering's classification system into one that ranked stars by their temperature into groups labelled O, B, A, F, G, K and M. A story was told at the observatory that Jump Cannon could remember every serial number of every photographic plate she had analysed – if true, a remarkable feat given she classified over a quarter of a million plates.

Pickering described her contribution to astronomy as "a structure that probably will never be duplicated in kind or extent by a single individual". Her peer, Cecilia Payne-Gaposchkin (see page 13), described Jump Cannon as the happiest person she had known. Though Jump Cannon had no children herself, she would hold parties for young people at her home in the Observatory estate, Star Cottage.

Leavitt's pulsing stars

Henrietta Swan Leavitt worked for Pickering and, like Jump Cannon, had a hearing impairment. At this time, women were typically not allowed to operate telescopes so she worked cataloguing and comparing photographic plates of stars. Payne-Gaposchkin argued that not allowing Leavitt to use telescopes "was a harsh decision, which condemned a brilliant scientist to uncongenial work, and probably set back the study of variable stars for several decades".

Leavitt made an important discovery about the relationship between the period of pulsation and luminosity of Cepheid variable stars, providing a 'standard candle' for astronomers to use to measure distances.

In addition, she discovered some 2,400 variable stars, around half the catalogue of such objects known in 1930. Leavitt died before the significance of the period-luminosity relationship she discovered was fully appreciated but Hubble claimed her research should have won the Nobel Prize.

Space

The axis of evil

The cosmic microwave background radiation is nearly uniform in all directions. However, in 2003, data from NASA's Wilkinson Microwave Anisotropy Probe found an unexpected pattern in the temperature data, which the journal *Nature* listed, in 2015, as one of six baffling physics results that can't be resolved. At one scale, the random fluctuations of the radiation seem to align in a preferred direction that has been dubbed the 'axis of evil' as it threatens models of the nature of the background radiation. A second anomaly in the data is the so-called 'cold spot', an area along the 'axis of evil' with a temperature around 70 μK less than the mean temperature of the background radiation. The 'cold spot' has been associated with a billion-light-year-diameter 'supervoid', a huge empty space that is devoid of galaxies.

Cosmic analogies

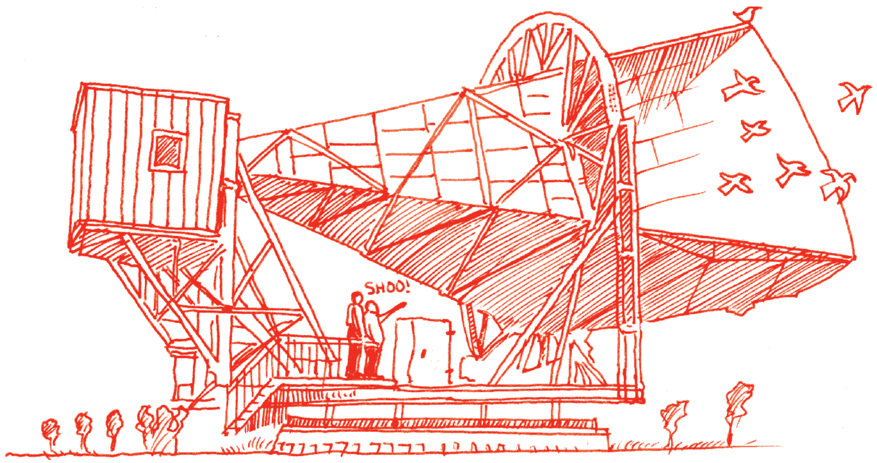
The Belgian Jesuit priest, Georges Lemaître, is credited with proposing the idea of the expanding universe. Lemaître used the analogies of a 'cosmic egg' and a 'primordial atom' to illustrate his ideas. In 1949, Fred Hoyle was invited to speak on the BBC Third Programme (the fore-runner of Radio 3) and, in making his argument for continuous creation of the universe, coined the term *Big Bang*. In his model of the expanding universe, Hoyle argued that "in a volume equal to a one-pint milk bottle, about one atom is created in a thousand million years".

The phantom planet

Following William Herschel's discovery of Uranus in 1781, it was noted that the planet's orbit was being perturbed. From these small deviations, the French astronomer Urbain Le Verrier predicted the existence of Neptune, which was subsequently confirmed through observation. Le Verrier next turned his attention to perturbations to the orbit of Mercury and predicted that an additional inner planet existed. A French doctor and amateur astronomer, Edmond Lescarbault, claimed to have seen this planet transit across the Sun, carrying out observations with a small telescope, recording them on planks of wood and using a watch missing one of its hands to time the events. Despite his crude tools, Le Verrier accepted that Lescarbault's observations confirmed the existence of the new planet. He named the body 'Vulcan' and died believing that he had discovered a new planet. After his death, sightings of the planet continued to arrive: two American observers noted a dim object close to the Sun and the *New York Times* reported that the "Planet Vulcan... appears at last to have been fairly run down". However, observation during eclipses at the start of the twentieth century failed to find the planet and, in 1915, Einstein's theory of general relativity explained the perturbation to Mercury's orbit, making the planet Vulcan superfluous.

White dielectric material from pigeons

Robert Penzias and Arno Wilson initially had no intention to look for evidence of the Big Bang but were interested in measuring the intensity of radiation from a supernova remnant. Having set up a horn antenna with a device to filter out noise by comparing the collected signal against a cold load, a Dewar of liquid helium at 4.2K, they were surprised to detect a microwave signal across all areas of the sky. In looking for sources of the noise they evicted some pigeons from the telescope and cleaned off from the instrument what Penzias described as a 'white dielectric material' left by the birds. The cleaning, however, failed to eliminate the noise from the signal.



Penzias and Wilson did not know the source of the microwave signal their telescope had picked up. But by coincidence, less than 30 miles away, a team led by Robert Dicke at Princeton had predicted that the Big Bang would result in microwave background radiation and had built a radiometer to detect the radiation. In 1965, Penzias mentioned the signal he had observed with Wilson to a colleague who had read a paper by a member of Dicke's team. After the conversation, Penzias rang Dicke, who took the call whilst he was having lunch with colleagues in his office and, on completing the call, Dicke turned to his team and said: "Well boys, we've been scooped."

Raspberry flavoured Milky Way

Radio astronomers examining dust clouds at the centre of our galaxy have found evidence of the chemical ethyl formate, which is responsible for the flavour of raspberries. The compound has an additional sensory property – it smells of rum.

The dwarf planets

The classification of objects in the solar system used to be simple – there was the Sun, nine planets and various smaller objects such as asteroids. In 2006, the International Astronomical Union (IAU) introduced the category of 'dwarf planets' to which Pluto was reclassified. Dwarf planets are defined as objects similar to planets in that they must orbit the Sun and be large enough that gravitational forces have formed the body into a nearly spherical shape. However, dwarf planets are not large enough to clear their orbits, that is, they do not remove smaller bodies from their path through collisions or gravitational capture. There are five generally accepted trans-Neptunian (ie orbiting on average at a greater distance from the Sun than Neptune) dwarf planets: Pluto, Eris, Sedna, Haumea and MakeMake.

How Hubble destroyed the universe

In 1920, a discussion took place during the American National Academy of Science's Annual Meeting. It quickly became known as the Great Debate and centred around the scale of the universe.

Through observations, astronomers had discovered objects that they called spiral nebulae. We now know these objects as galaxies but, at the time, their nature was unclear. Harlow Shapley, of the Harvard College Observatory, argued that spiral nebulae were located within the Milky Way and were simply giant clouds of dust and gas. On the other side of the debate, Heber D. Curtis put forward the case that these objects exist outside the Milky Way and that the universe is made up of many spiral nebulae, each an 'island universe' composed of billions of stars.

The debate was settled, a few years later, by Edwin Hubble (see page 4). He used Henrietta Swan Leavitt's (see page 15) variable star period-luminosity relationship to calculate the distance to the Andromeda 'nebula' and hence showed it existed outside of the Milky Way. This led to the realisation that 'spiral nebulae' were galaxies just like our own.

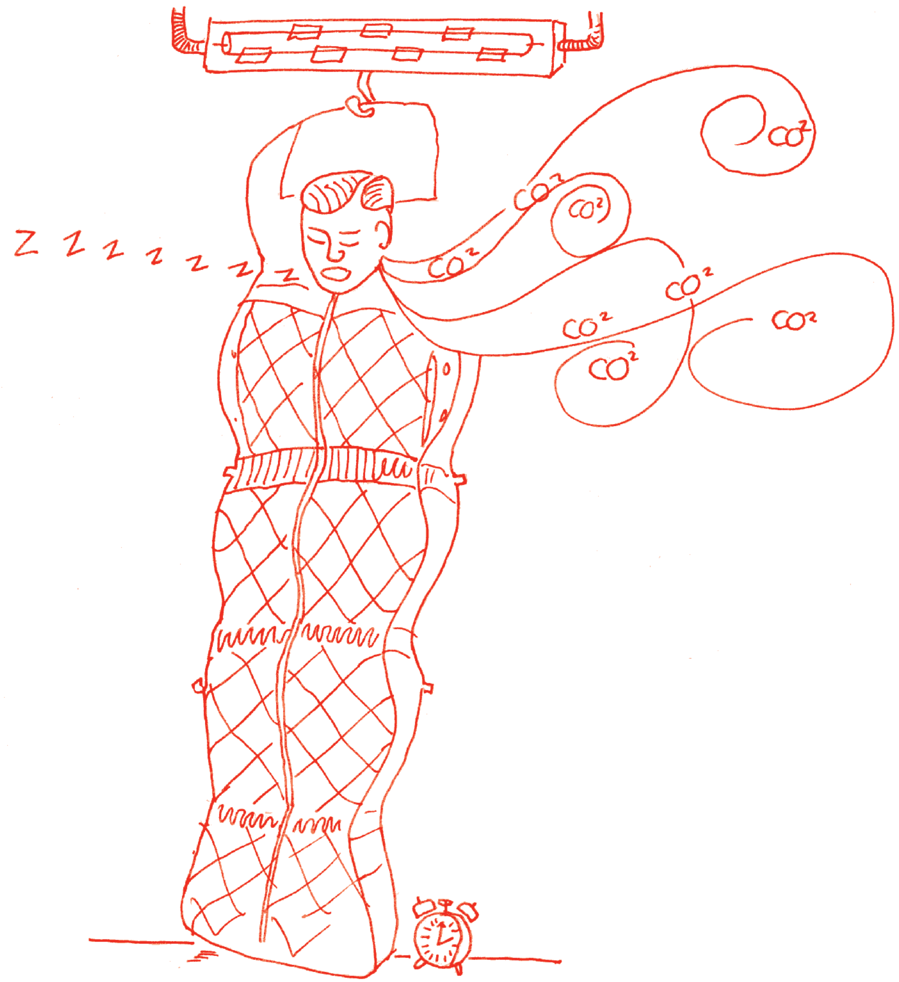
Shapley and Hubble had long been rivals. When Shapley received the news of Hubble's data, he is reported to have commented: "Here is the letter that has destroyed my universe."

The origins of Space Camp

The idea for the popular children's 'Space Camp' run by NASA was first proposed by Wernher von Braun who had worked as a rocket engineer for the Nazi regime. Von Braun developed the prototype V2 rocket engine and, at the end of the war, surrendered to American forces. He was transferred to the United States where he worked first for the Army Ballistic Missile Agency and later as a program director at NASA.

Sleep suffocation

Astronauts on the International Space Station must sleep by a ventilator. The microgravity on the spacecraft means exhaled carbon dioxide does not move away from a sleeping astronaut and, without air circulation, they could suffocate in a bubble of their own carbon dioxide.



A star is born - and eventually dies

The next sections contain stories about the different stages in a star's life cycle: nebulae, main sequence stars, red giants, white dwarfs, supernovae, neutron stars and black holes. You can see these illustrated on pages 26-27.

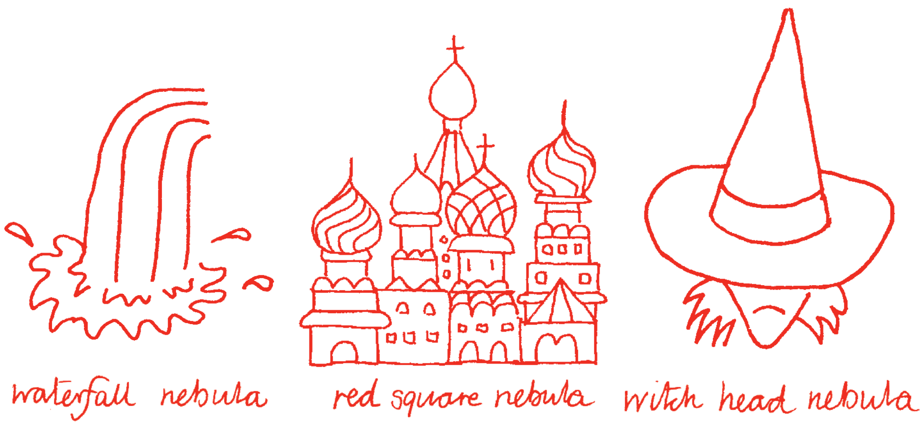
Nebulae

Colourful nebulae

Nebulae are known for their bright colours, an effect which can occur through different processes.

- *Emission nebulae* consist of a cloud of ionised gas containing or close to some very bright stars emitting ultraviolet (UV) radiation. The UV radiation is absorbed by the gas and leads to the excitement of electrons, which in turn leads to the emission of visible light. Most emission nebulae appear deep red due to emission at the hydrogen α-line at 656 nm.

- *Reflection nebulae* are visible as they reflect light from other stars. Reflection nebulae appear blue due to the same kind of scattering of light that makes the sky appear blue.



Viral star birth

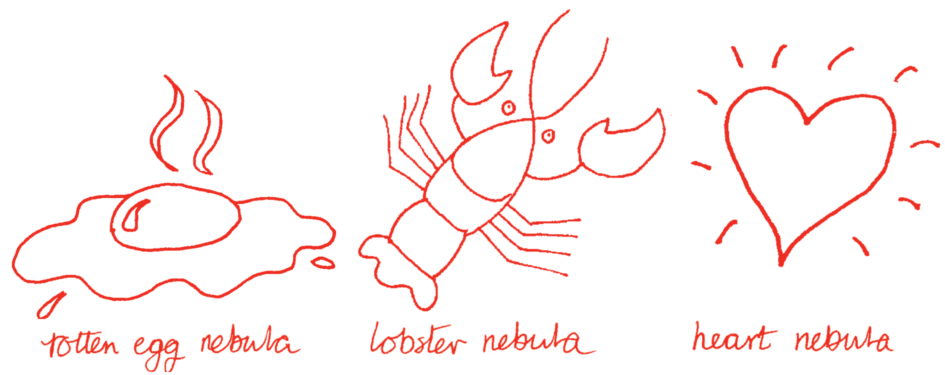
Star formation in nebulae can be contagious. When large stars are formed in a nebula, the intense radiation produced can compress the surrounding gas and cause the formation of more stars. The shockwave resulting from a supernova can also trigger the collapse of gas in a nebula and seed the formation of new stars.

Star cocoons and other nebulae nuggets

- A *protostar* is a body of gas that is compressed enough to be opaque but not hot enough to allow nuclear fusion to begin. As material flows into a protostar, a cloud of enveloping gas known as a cocoon nebula may form.

- The shapes of nebulae have attracted some curious names including: the *Waterfall Nebula*, the *Lobster Nebula*, the *Witch Head Nebula*, the *Red Square Nebula* and the neighbouring *Heart and Soul Nebulae*. The *Calabash* or *Rotten Egg Nebula* is named for the high levels of sulphur found in its gases.

- The density of gas in nebulae is typically very low - one analogy suggests imagining the quantity of gas in a typical village hall expanded to the volume of the Earth.



The lost pillars of creation

Perhaps one of the most well-known structures in a nebula is 'the pillars of creation' in the *Eagle Nebula*. The 'fingers' are composed of cold molecular hydrogen and dust.

A team of French astronomers have claimed that a shockwave from a supernova that occurred 6,000 years ago destroyed the pillars and that the structure will only be visible for another 1,000 years from the Earth. This finding is disputed by Stephen Reynolds, an American astrophysicist, who disagrees that the hot dust cloud taken as evidence of a supernova by the French team indicates the occurence of such an event.

Herschel's hole in the sky

When William Herschel was observing the night sky, he noted that, in some areas, there appeared to be 'a hole in the sky'. The nature of these dark areas was not understood till the 1940s when Dutch-American astronomer Bart J. Bok proposed that they were areas of star formation, sometimes called *dark nebulae*. One such region is the molecular cloud Barnard 68. These compact and spherical dark objects of extremely low temperature, now named *Bok globules,* are not well understood and remain the subject of research.

The coldest place in the universe

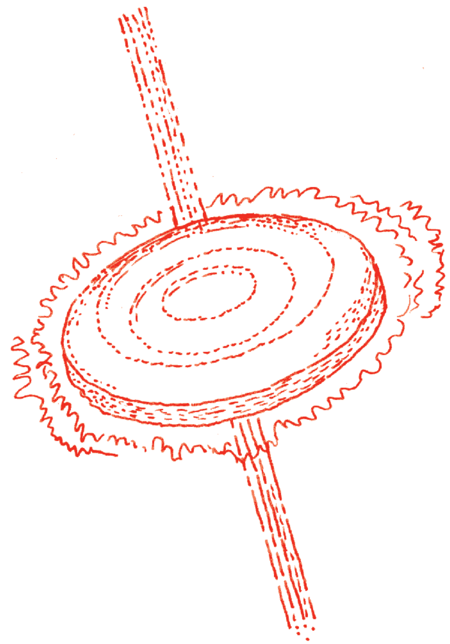
A young planetary nebula, the *Boomerang Nebula,* is the coldest naturally occurring place in the universe at a temperature of 1 K. The low temperature of the nebula is thought to arise from the rapid expansion of gases, travelling at speeds of around 160 km/s.

Protostar physics

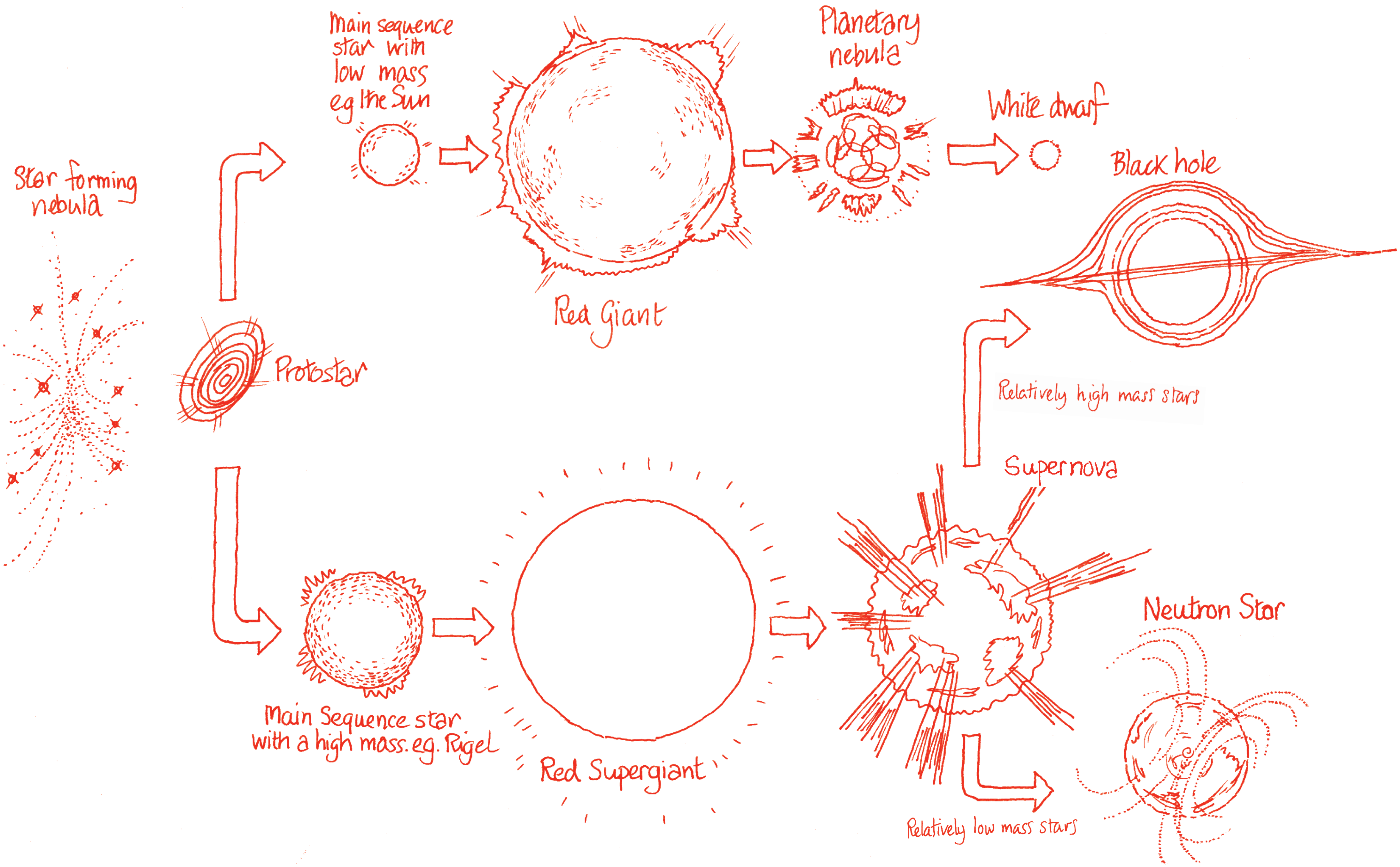
- During the initial collapse of a nebula into a protostar, the temperature of the collapsing material is low, typically around 30 K. During this stage, the protostar may occupy a sphere with a radius of around 1000 astronomical units (one astronomical unit is approximately the distance from the Earth to the Sun which equates to about 200 times the distance to Pluto at its furthest from the Sun). The protostar remains shrouded in a cloud of dust and gas and only radio emissions are detectable from this phase of its development. As the protostar collapses, it develops a magnetic field which increases in intensity as the star's size decreases. Observations from satellite X-ray observatories have detected unexpectedly intense X-ray radiation emanating from cold protostars. It is speculated that the magnetic fields of protostars accelerate matter to high velocities (up to 2000 km/s). When the accelerated material collides with the protostar, X-rays are emitted. The process that generates the magnetic fields is still the subject of speculation – one explanation is a dynamo-effect-like process.

- Protostars can fire out jets of material: in 2011, data collected by the European Space Agency's Herschel Space Observatory showed evidence of a protostar, dubbed the 'stellar sprinkler', emitting jets of hydrogen and oxygen at velocities of 200,000 km/hr.

- Astrophysicists have recently succeeded in imaging a dusty accretion disc that surrounds a very young protostar. They describe the disc as having a 'hamburger-shaped' appearance. HH 212, a very young protostar (around 40,000 years old) in the constellation of Orion, has in addition to an equatorial disc, two powerful jets of materials emanating from its poles.



The life-cycle of a star



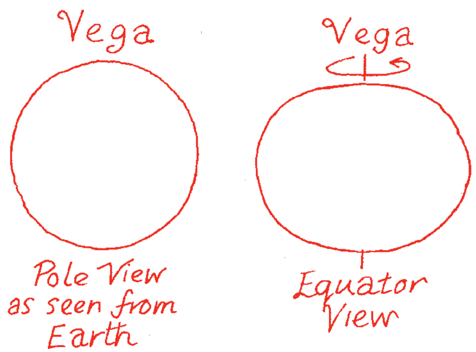
Main Sequence Stars

Where are the green stars?

For a star to emit most radiation in the green wavelength it would require a surface temperature of around 6000 K. But it would then also emit similar amounts of blue and red light resulting in a white or pale-yellow colour, like the Sun. So there are no green stars.

The bulging star

Vega is the fifth brightest star in the sky. Its radius is nearly three times that of the Sun, but because it is spinning over a hundred times faster at 2.7 x 10^5 m/s, it has a distinct equatorial bulge.



Ancient photons

It typically takes around 500,000 years for a photon to be emitted from the solar interior. The interior of the Sun consists of high-density plasma which absorbs and re-emits photons as they travel. A photon would travel only 10^{-4} m before being absorbed and then re-emitted in a random direction. On average, it will have to make 49 x 10^{24} steps in order to be emitted.

Exotic stars

A number of theoretical exotic stars have been proposed including:

- *Quark stars* - result from the decomposition of component neutrons
- *Strange stars* - quark stars that contain strange quarks
- *Electroweak stars* - in which gravitational forces are balanced by radiation from electroweak decay
- *Planck stars* - in which quantum gravitational pressure causes a ‘bounce’ whilst the stars are collapsing to form a black hole.

Spotting sunspots

- There is evidence of observation of sunspots in ancient Greek and Chinese astronomical records. One of the earliest telescopic observations of the phenomenon was made by amateur father-and-son observers David and Johannes Fabricius in 1610. On David’s birthday, the pair noted dark spots on an image of the Sun projected through a telescope. Johannes published an essay on his discovery, preceding Galileo’s description of sunspots by a year. The pair did not survive to see the impact of their discovery - Johannes died four years later and his father was murdered shortly after by a farmer whom Fabricius had accused of stealing a goose.

- Whilst to the Earth-based observer, sunspots look like small black spots on the surface of the Sun, their appearance is deceptive as they are perceived in relation to the Sun. Sunspots can have a diameter of up to 100,000 km and have temperatures of around 4,300 K. Seen in isolation, a sunspot would be around a hundred times as bright as the full Moon and only seem dim in comparison to the surrounding surface of the Sun.

- The Sun’s magnetic field can reverse at times of maximum sunspot activity. In 2001, the solar magnetic field suffered such a change and the reversals are hypothesised to follow the 11-year cycle of sunspot activity.

Tabby’s star

Unusual fluctuations in the luminosity of an F-type main sequence star, known as Tabby’s star (after the lead author of the initial study Tabetha Boyajian) have led to a flurry of speculation about their cause. The star’s brightness dips aperiodically by up to 20%, with the reductions lasting between 5 and 80 days. The Penn State University astronomer Jason Wright proposed that the fluctuations could be explained by an alien ‘megastructure’ and added: “Aliens should always be the very last hypothesis you consider, but this looked like something you would expect an alien civilization to build.” Other astrophysics have since concluded that the most likely explanation for the fluctuations is that the star is surrounded by a swarm of comets or fragments of bodies too small to become planets. The orbiting objects absorb radiation, explaining the changes to luminosity.

Red Giants

The big dog

One of the largest known giant stars, VY Canis Majoris, is 30-40 times more massive than the Sun and 500,000 times more luminous. If it were placed in the solar system in the position of the Sun, its surface would extend beyond the orbit of Jupiter. The star is in the process of shedding mass prior to exploding in a supernova. VY Canis Majoris is so large it would take light 8.5 hours to travel round its circumference (by comparison with the 14.5 seconds it would take light to circumnavigate the Sun's equator).

Living with a red giant

It has been suggested that once a main sequence star transitions into a red giant, life might develop in the habitable zone of the newly formed giant star. For a star of the mass of the Sun, the habitable zone may move out to between 2 - 9 astronomical units (one astronomical unit is approximately the distance from the Earth to the Sun) during the first stage of evolution after leaving the main sequence and then up to as far as 22 astronomical units from the star after the core helium flash. It has been predicted that Titan, the largest moon of Saturn, may become a habitable planet following the transition of the Sun into a red giant.

Starquakes

Sound waves can cause the brightness of stars to vary over periods of 5-15 minutes. Astroseismology is the study of such internal vibrations of stars. Just as seismologists can use data about the travel of seismic waves to learn about the structure of the Earth, astroseismologists develop models of stars' internal structures from the passage of seismic waves.

For example, astroseismology has been used to develop models of the magnetic fields present in red giant stars. Observations of vibrational data made using the Kepler Space Telescope revealed that the cores of red giant stars rotate ten times faster than their surfaces. At the boundary of the dense core of a red giant, seismic waves travelling in the outer layers of the star are transformed into gravity waves. The propagation of gravity waves can be influenced by the presence of strong magnetic fields. A 'magnetic greenhouse effect' occurs in the cores of red giant stars

in an analogous way to the manner in which the Earth's atmosphere traps radiation. The strong magnetic field of the core of a red giant causes gravity waves to become trapped in the star's core. Observations of the oscillation modes of red giant cores have led to astronomers inferring the presence of magnetic fields of up to 1000 T.

Cannibal stars

A strange type of star was hypothesised by two astronomers in the 1970s and labelled *Thorne-Żytkow objects* (TŻO). Kip Thorne and Anna Żytkow noted that most massive stars are part of binary systems and wondered how a binary system consisting of a neutron star and another star would evolve over time. They predicted that, in some cases, the distance between the stars would gradually diminish. The neutron star could then be absorbed by its companion star as, by this stage, it is likely to have evolved into a mature red giant at this stage. Given the large number of older stars in the galaxy, it is estimated that 1% of red supergiants may have absorbed neutron stars to become TŻOs. The stars have therefore been referred to as 'cannibal stars'.

Betelgeuse, the red super giant in the shoulder of the constellation of Orion and just 430 light years from Earth, may have swallowed a companion star. As a star expands to form a red giant, conservation of angular momentum predicts its rotational velocity will decrease. Betelgeuse is spinning 150 times faster than could be explained by the normal pattern of stellar evolution. A computer model suggests the rapid rotation may be explained if Betelgeuse absorbed an orbiting companion star and so received additional angular momentum. Betelgeuse is due to supernova, though it is difficult to predict when - it may occur at any time in the next 100,000 years.

The red giant problem

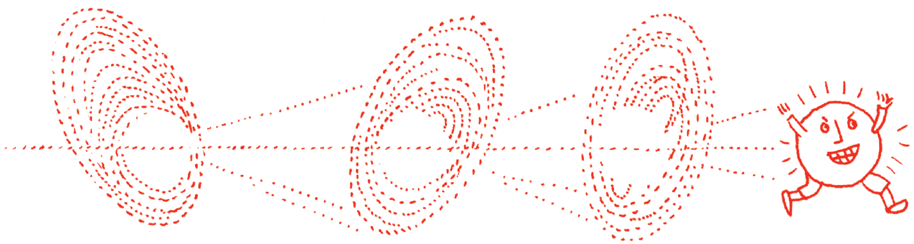
Astrophysicists struggled to understand how red giant stars could be very much more luminous than main sequence stars that were at similar effective temperatures – the so-called 'red giant problem'. The problem arose early in the 1900s partly because Sir Arthur Eddington's influential stellar models had assumed that stars were homogeneous. At the end of the 1930s, Ernst Öpik (see page 36) suggested that nuclear fusion might occur only in a shell beyond the core of the red giant, leading to the resolution of the problem and the development of better models of the giant stars.

Echoing light

Among the many beautiful images produced by the Hubble Space Telescope, some of the most dramatic are the sequence of images capturing a flash of radiation from a red supergiant star, V838 Mon, in the Unicorn constellation. In 2002, the star suddenly increased in luminosity, releasing a burst of radiation 600,000 times more luminous than the Sun. The Hubble telescope captured a series of images of this radiation lighting up dust and gas surrounding the stars. The stunning sequence of images is viewable at the NASA website: nasa.gov/content/discoveries-highlights-seeing-light-echoes

Galactic harassment

In 1998, astrophysicists observed the effects of 'galactic harassment' - the effect of multiple, close, high-speed encounters between massive galactic clusters. The Hubble Space Telescope is sensitive enough to detect the diffuse light from stars that exist between galaxies, known as *extragalactic stars*, and the researchers identified a group of red giant stars that had been ripped from their galaxies.



The polystyrene planet

Astrophysicists have discovered an 'extraordinarily inflated' low-density exoplanet. KELT-11b has a radius around 1.4 times that of Jupiter but only about a fifth of its mass, giving it a density of only 0.09 g/cm^3, around the density of Styrofoam. KELT-11b orbits close to its parent star and has an orbital period of just five days. The parent star is in the process of expanding into a red giant and is likely to engulf its low-density satellite within a hundred million years.

A neighbourly red giant

Red giants may become unstable and exhibit variable luminosity: the red giant Mira (Omicron Ceti) displays a variation in luminosity by a factor of 10,000 over a period of 11 months and can be seen with the naked eye when at maximum brightness. The diameter of the star's atmosphere changes by roughly 100 million kilometres during the cycle of pulsation.

Observations have also noted a giant flare from the star. Mira is part of a contrasting binary system consisting of two stars, both with similar masses to the Sun, one a white dwarf, the other a red giant. It is speculated that such flares may be one mechanism by which heavier elements such as carbon, oxygen and nitrogen that are produced in fusion in red giants are distributed in the universe.

White Dwarfs

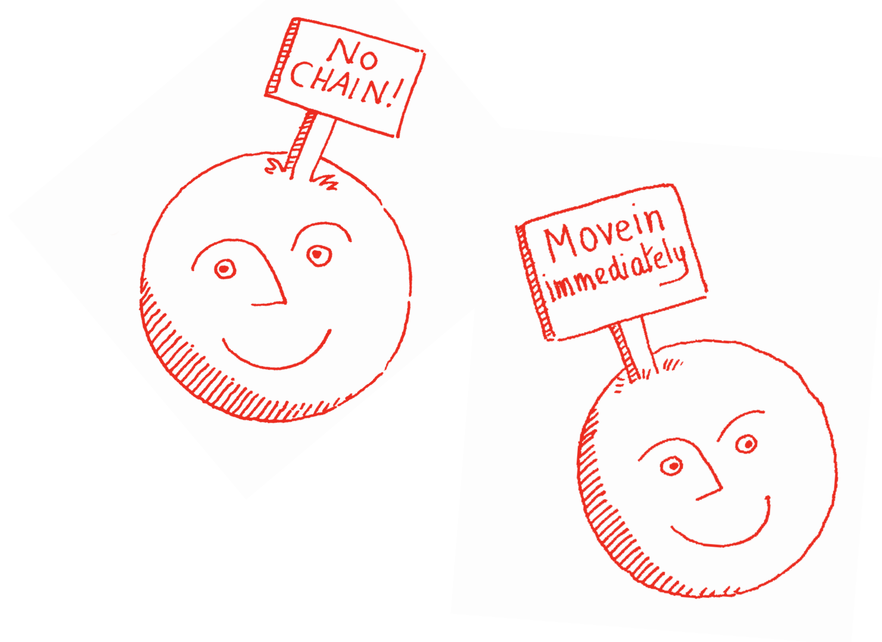
The only people to know about white dwarfs

Henry Norris Russell (co-developer, with Ejnar Hertzsprung, of the eponymous diagram) described the moment of discovery of White Dwarf stars in 1910. Russell had suggested an analysis of the low luminosity star, Omicron Eridani, which was unusual since its spectrum resembled that of a much hotter star. Russell had proposed to his colleague, Edward C Pickering, working with Williamina Fleming (see page 14) that it would be useful to measure the spectra of a star of known distance...

> And so we telephoned down to the office of Mrs. Fleming and Mrs. Fleming said, yes, she'd look it up. In half an hour she came up and said, "I've got it here, unquestionably spectral type A." I knew enough, even then, to know what that meant. I was flabbergasted. I was really baffled trying to make out what it meant. Then Pickering thought for a moment and then said with a kindly smile, "I wouldn't worry. It's just these things which we can't explain that lead to advances in our knowledge." Well, at that moment, Pickering, Mrs. Fleming and I were the only people in the world who knew of the existence of white dwarfs.

Favourable habitable planets

The development of new observational techniques has seen an increase in reports of exoplanets, planets that orbit stars other than the Sun. The launch of the Kepler Space Telescope which monitors the brightness of over 145,000 main sequence stars has led to a spike in the discovery of exoplanets with 700 new exoplanets discovered in 2014 alone. One of the most interesting exoplanet discoveries was reported in early 2017: astronomers found evidence of seven temperate planets, of masses and sizes similar to the Earth, orbiting a cool, Jupiter-sized dwarf star. The host star, named TRAPPIST-1, is 39 light-years away and has a mass just 8% of the Sun. The dwarf star is relatively cool with a surface temperature of around 2,600 K. The planets have orbital periods ranging from 1.5 days to just over 12 days and have surface temperatures in the right range to allow the presence of liquid water. A 2020 paper described the TRAPPIST-1 system as: "[t]o date, ... the most observationally favourable system of potentially habitable planets known to exist".

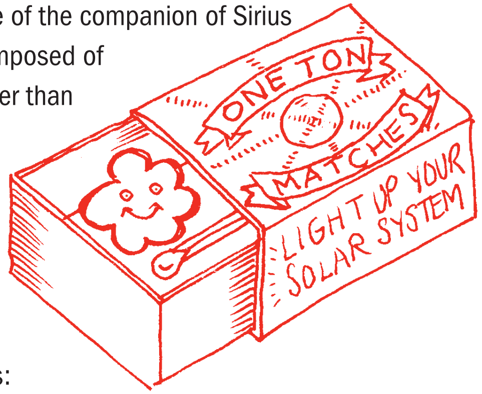


Surprisingly dense stars

The high density of white dwarf stars was a surprise to astronomers. The Estonian astronomer Ernst Öpik (grandfather of the former British Liberal Democrat MP Lembit Öpik) calculated the density of Sirius B - now known to be a white dwarf - and declared the answer "impossible". Öpik is also to be credited for postulating the idea of the Oort cloud, a shell of icy objects beyond the edges of the solar system, before it was suggested by Oort.

Eddington expressed his shock at the density of white dwarfs in a lecture:

> We learn about the stars by receiving and interpreting the messages which their light brings to us. The message of the companion of Sirius when it was decoded ran: "I am composed of material three thousand times denser than anything you have ever come across; a ton of my material would be a little nugget that you could put in a match-box." What reply can one make to such a message? The reply which most of us made in 1914 was: - "Shut up. Don't talk nonsense."

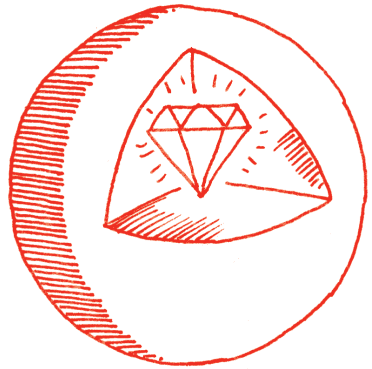


Binary brightness

White dwarf stars may form binary systems with other stars (see above) which have typical orbital periods of 1-10 hours. These systems are known as *cataclysmic variables* as the second star loses material to the dense white dwarf by accretion (the growth of an astronomical body by the addition of mass through gravitational attraction), releasing X-ray radiation. The second star is usually a late main sequence star or a red giant and the accretion process leads to an abrupt increase in brightness of the system over a time period of a day followed by a reduction in luminosity that can last from weeks to several months – a process referred to as a type Ia supernova (see page 47).

Thin skies but a diamond at heart

The matter inside white dwarf stars is crushed in an incredibly strong gravitational field. This leads to *electron degeneracy,* a state of matter in which electrons are so strongly squeezed together that a force is exerted because the particles are forbidden from occupying the same quantum state. It is thought that some white dwarfs have almost pure hydrogen or helium atmospheres as heavier atoms sink in the strong gravitational field. The gravitational field means that the stellar atmosphere is so thin that, if it were on Earth, the top of the atmosphere would be lower than the tops of skyscrapers. Beneath a 50 km crust, it is hypothesised that the core of white dwarf stars may consist of a crystalline lattice of carbon and oxygen, which has been compared to the structure of diamond.



Small but very hot

White dwarfs can be very small, some just half the radius of the Earth, yet the stars can reach incredibly high temperatures of up to 200,000 K. It is estimated that around 10% of all stars are white dwarfs though this figure is speculative as the stars are hard to detect.

Chandrasekhar's 'stellar buffoonery'

Whilst travelling by sea from India to England to continue his studies at Cambridge in 1930, Subrahmanyan Chandrasekhar had nothing to do but think and study so, naturally, he chose to use the time to apply the theory of relativity to collapsing stars. He calculated that a star would become a white dwarf if it had a mass of less than 1.4 solar masses, reporting that his calculation was "so simple and elementary anyone could do it".

Once he arrived, Chandrasekhar found it difficult to settle into Cambridge, partly because of the prevalence of racial prejudice. He reported being "suffocatingly lonely" like a "single electron in deadly free space". To compound his isolation, Chandrasekhar's ideas met with disfavour from Arthur Eddington who used an address at a conference to critique his younger colleague:

> ... I felt the same objections as earlier to this stellar buffoonery; at least it was sufficient to rouse my suspicion that there must be something wrong with the physical formula used.

Eddington refused to accept Chandrasekhar's results commenting that: "I think there should be a law of nature to prevent a star from behaving in this absurd way!"

The dispute has been characterised as an 'uneven fight' between the 25-year-old Indian physicist, newly arrived in the country, and the distinguished and well-connected Eddington. Chandrasekhar reported his feelings of dismay:

> I felt that astronomers without exception thought that I was wrong. They considered me as sort of Don Quixote trying to kill Eddington... it was a very discouraging experience for me... to have my work completely and totally discredited by the astronomical community.

Despite the difficult initial reception of his ideas, Chandrasekhar's calculations are now widely accepted.

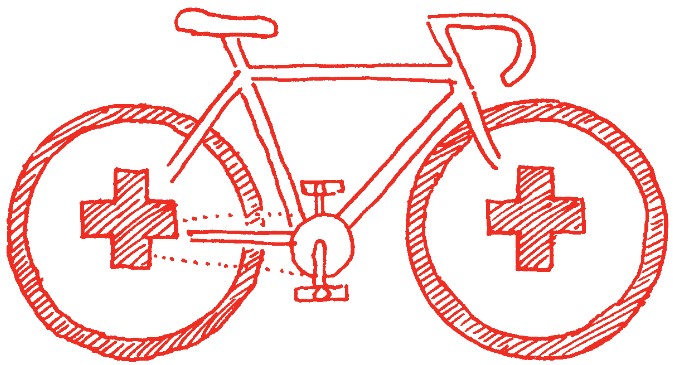
Stories from physics

Eddington numbers

In astrophysics, the Eddington number is the number of protons in the observable universe. He defined it as

$N_{Edd} = 136 \times 2^{256}$ which is approximately 1.575×10^{79}.

In addition to his scientific studies, Eddington was a keen cyclist, a hobby which led to his proposal of a different kind of metric. A Google search is more likely to bring up the Eddington number as the number of times a cyclist has cycled a particular distance in miles. For example, an Eddington number of 20 would indicate a cyclist had cycled more than 20 miles on 20 occasions.



Supernovae

The superlative superluminous supernova

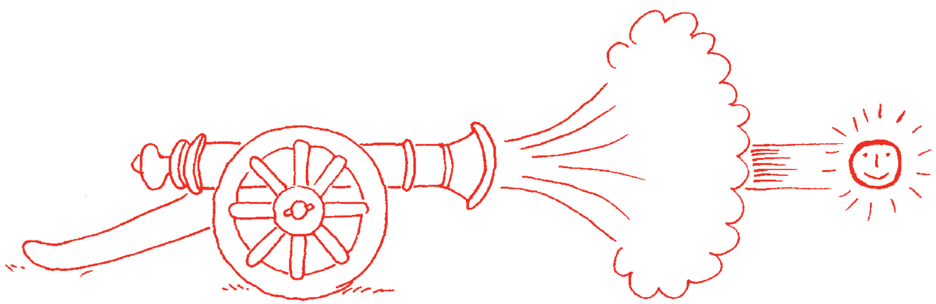
In 2016, astrophysicists reported the occurrence of one of the most luminous supernovae ever detected. The supernova shone with a brightness 20 times more intense than all the stars in the Milky Way or 600 billion times brighter than the Sun. The so-called 'superluminous supernova' was so unexpectedly bright it has challenged astrophysicists' models of how supernovae occur.

Naked-eye supernovae

The historical astronomical records from ancient China and Japan are believed to contain eight observations of supernovae and, impressively, are estimated to be 70% complete if naked-eye supernovae occur once every 175 years. Following the observations of supernovae in 1572 and 1604 by Brahe, Kepler and others, it is claimed that there has only been one further naked-eye supernova. This event occurred on the night of 23-24 February 1987 and was seen in the Large Magellanic Cloud.

The cannonball star

An unusual 'cannonball star' has been observed travelling at more than 1.54 million km per hour. The astrophysicists who observed the star believe it may have been ejected from a binary system in a supernova and carries traces of carbon formed in the exploded star.

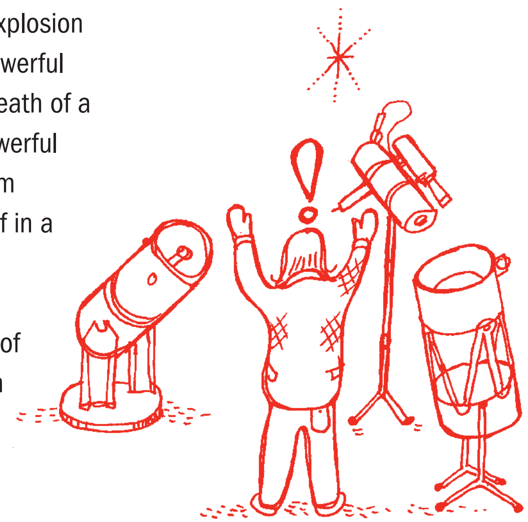


Icy supernovae

The effects of supernovae can be detected in Antarctic ice. Ionising radiation released from supernovae can form nitrate ions when it strikes the atmosphere, which are then detectable in ice-cores. The Vela pulsar is the remnant of a supernova which occurred around 11,000 - 12,000 years ago. Researchers from McGill and Dortmund Universities have used data from 20 year-old Antarctic ice core samples to estimate the supernova occurred in a star 15 times the mass of the Sun.

The little supernova

In 2008, one of the faintest supernovae ever recorded was detected by a 14-year-old amateur astronomer. Caroline Moore, from upstate New York, used a small telescope to image an unusual astronomical explosion which was a thousand times less powerful than a supernova (the destructive death of a star) but a thousand times more powerful than a nova (a release of energy from material accreted from a white dwarf in a binary system). A number of models have been proposed for the phenomenon including the collapse of a massive star into a black hole with limited radiation of energy.



Nuclear-fuelled supernovae

Not all supernovae result from the collapse of a red giant star: type Ia ("one A") supernovae occur when a white dwarf has accumulated sufficient matter to exceed the Chandrasekhar limit (any white dwarf with less than this limit – 1.4 times the mass of the Sun - will stay a white dwarf forever, while a star that exceeds this mass is destined to become a supernova). The explosion is driven by the fusion of carbon into iron by a 'nuclear burning front,' which travels through the star. Though much material will be dispersed during this explosion, simulations suggest it is possible that a bound remnant will remain. In such thermonuclear supernovae, nuclear decay plays a role in the brightness of the event. As fusion progresses, nickel-56 is produced. This decays into cobalt-56 with the release of gamma rays, which excite surrounding nuclei of oxygen, silicon, sulphur and calcium. These nuclei then emit radiation, increasing the brightness of the supernova explosion. Peak brightness of this kind of supernova typically occurs two to three weeks after the onset of the supernova and decreases as levels of nickel-56 fall. The cobalt-56 gradually decays into iron-56 leading to a gradual decrease in brightness of the supernova.

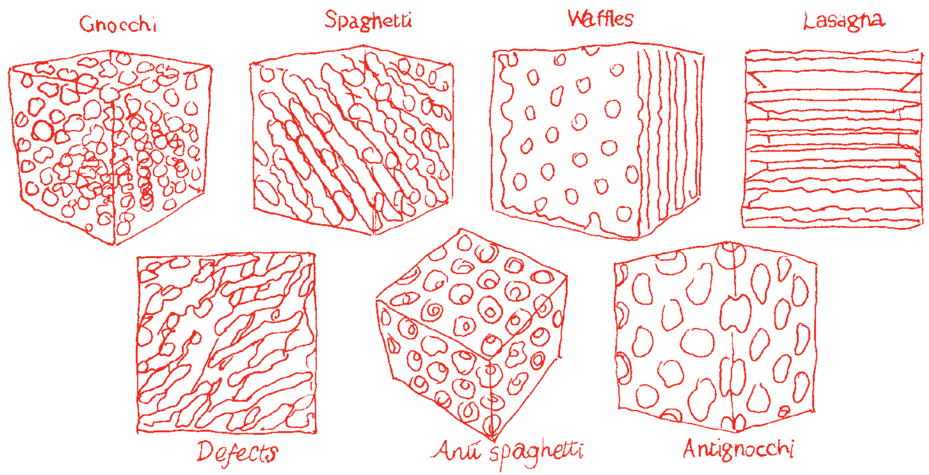
Listening to the stars

A blind astronomer, Dr Wanda Diaz Merced, has developed an approach to turning astronomical data into auditory signals, known as sonificiation. It's well worth listening to her TED talk is at: ted.com/talks/wanda_diaz_merced_how_a_blind_astronomer_found_a_way_to_hear_the_stars. Harvard's Professor Alicia Soderberg has applied sonification to supernovae data, teaming up with musicians and visually impaired scientists, leading to new insights into the events.

Neutron Stars

Nuclear pasta

A star with a mass similar to the Sun may form a neutron star with a diameter of around 20 km. The surface of such a neutron star is modelled as consisting of a form of iron 10,000 times as dense as iron on Earth and beneath the surface is a mantle-like layer of liquid neutrons. The layers of the inner crust of neutron stars can undergo a series of transitions between different nuclear structures; the resemblance of these structures to spaghetti and lasagne has led researchers to refer to them as 'nuclear pasta'.



Neutron stars' mini-mountains

Strong gravitational forces cause neutron stars to be almost perfectly spherical - if a typical neutron star were expanded to the size of the Earth, there would be no mountains higher than 10 m above sea level on its surface.

Bell Burnell's brilliance

In an after-dinner speech, Jocelyn Bell Burnell reported the research in 1967 that would lead to the discovery of the pulsar. She described the work to build the Interplanetary Scintillation Array on the outskirts of Cambridge. Eager students were recruited over the summer to sledgehammer over a thousand posts into a 4½ acre field. The posts were strung with 120 miles of wire to create a radio telescope.

She reported seeing a bit of 'scruff' on one of the recordings from the telescope and trying to make another observation of the same area of sky, but she couldn't detect a signal and assumed that the source had vanished. However, she later found the signal again and discovered it consisted of equally spaced pulses at 1⅓ second intervals. Her supervisor, Tony Hewish, suggested that the signal must have an artificial source, but Bell Burnell believed that it might come from a star. She acknowledged that Hewish's response was the more sensible and said her own belief was driven by a "truly remarkable depth of ignorance".

Stories from physics

Bell Burnell repeated the observation, having to breathe on the receiver system to get it to work properly in the cold Cambridgeshire winter. She was able to confirm the presence of the source which was temporarily labelled LGM-1 (Little Green Man 1). The signal was established to be a rapidly rotating neutron star emitting radiation: a pulsar.

Once the findings were announced, journalists descended on Cambridge but asked the young scientist questions which reflected attitudes to female researchers at the time, rather than showing a genuine interest in the discovery. Bell Burnell recalls being asked: "Was I taller than or not quite as tall as Princess Margaret… and how many boyfriends did I have at the time?" The photography also failed to reflect the significance of her work – Bell Burnell reports being asked to take up "several silly poses: standing on a bank, sitting on a bank, standing on a bank reading bogus records, sitting on a bank reading bogus records, running down a bank waving her arms in the air".

When her supervisor and another scientist received the 1974 Nobel Prize for the discovery, Bell Burnell was not included in the award. She later commented stoically:

> First, demarcation disputes between supervisor and student are always difficult, probably impossible to resolve. Secondly, it is the supervisor who has the final responsibility for the success or failure of the project. We hear of cases where a supervisor blames his student for a failure, but we know that it is largely the fault of the supervisor. It seems only fair to me that he should benefit from the successes, too. Thirdly, I believe it would demean Nobel Prizes if they were awarded to research students, except in very exceptional cases, and I do not believe this is one of them. Finally, I am not myself upset about it - after all, I am in good company, am I not!

Seeing all the star

Given a compact enough neutron star, the effects of gravitational lensing mean that the entire surface of the object can be visible to an observer at one time. Science writer Stan Gibilisco has described what an observer might see if they were unfortunate enough to be on the surface of a neutron star as it continued to collapse:

> At first, everything would appear to be quite normal... But as the intensity of the gravitational field became greater and greater, and the geometric distortion of space increased, the sky would change. New stars, previously invisible because they were below the horizon, would appear to rise upward from the horizon at all points of the compass. All the stars in the sky would seem to be moving upward toward the zenith... Finally the horizon would heave upward, and you would get the feeling of being at the bottom of a huge bowl... The whole horizon would retreat to the zenith, and close off your view of the outside heavens completely.

Glitchy pulsars

The fastest rotating pulsar, PSR J1748-2446ad, has a rotational frequency of 716 Hz. Though the rotational periods of neutron stars are typically regular, some stars experience small changes in frequency known as glitches. These glitches are thought to arise from starquakes which are the result of rotational deformation stressing the surface of the star. Under stress, the surface can crack suddenly, leading to a change in shape and a glitch.

Pulsar sat-nav

It has been proposed that pulsars could be used as a kind of beacon to orientate spacecraft. A spacecraft could detect the beams of X-ray radiation emitted by a number of pulsars and compare their arrival time to calculate its position within the galaxy, in a similar manner to how satellites are used in GPS systems.

Zwicky's modesty

In 1932, James Chadwick discovered the neutron and Lev Landau predicted the existence of neutron stars. Two years later, the Bulgarian/Swiss astronomer Fritz Zwicky developed Landau's concept and made some detailed predictions about their behaviour. His seemingly outlandish ideas were lampooned in an Associated Press cartoon 'Be Scientific With OL'DOC DABBLE'. The caption of the cartoon read:

> Cosmic rays are caused by exploding stars which burn with a fire equal to 100 million Suns and then shrivel from 1/2 million mile diameters to little spheres 14 miles thick, says Prof. Fritz Zwicky, Swiss Physicist.

Four decades later, his ideas vindicated, Zwicky referred to the cartoon: "This, in all modesty, I claim to be one of the most concise triple predictions ever made in science."

An article describing Zwicky's contribution suggests that: "When researchers talk about neutron stars, dark matter, and gravitational lenses, they all start the same way: 'Zwicky noticed this problem in the 1930s. Back then, nobody listened...'." It is remarkable that Zwicky, with his colleague Baade, predicted the transition from supernova to neutron star in 1934, only two years after the discovery of the neutron. The pair are also responsible for coining the term 'supernova' to distinguish the events from ordinary novae.

Zwicky can also claim the creation of the first artificial meteors. He loaded rockets with high explosives which detonated after launch to generate jets of liquid metal and could then be photographed by astronomers to gain a better understanding of the formation of meteors. During one of these liquid metal experiments in 1957, one of the jets escaped the Earth and is thought to be the first artificial object to orbit the Sun.

Zwicky is reported to have been a pugnacious character - he referred to his enemies as "spherical bastards" because they looked like bastards from any angle. He even boasted to Millikan: "I have a good idea every two years. You name the subject, I bring the idea." However, he proposed a number of less successful notions, including a jet plane that could burrow through the Earth.

Black Holes

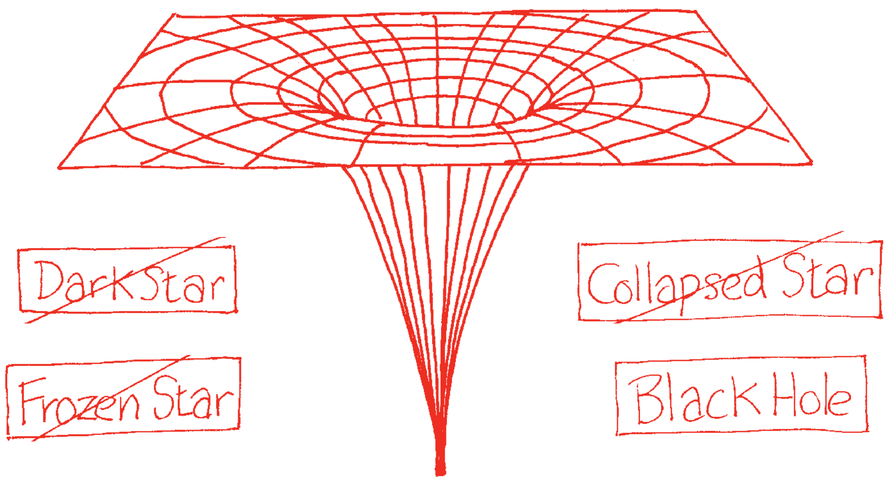
18th century black holes

Perhaps the earliest thinker to suggest the idea of black holes was an English reverend, John Michell. In 1724 Michell noted that:

> If there should really exist in nature any bodies whose density is not less than that of the Sun, and whose diameters are more than 500 times the diameter of the Sun, since their light could not arrive at us ... of the existence of bodies under either of these circumstances, we could have no information from sight.

Michell referred to these objects as 'dark stars'. Later scientists referred to black holes as 'frozen' or 'collapsed' stars.

The term *black hole* was coined in 1968 by American physicist John Wheeler. He famously quipped that "black holes have no hair" as models predict there are only three quantities that can be known them: their mass, angular momentum and charge.



The virtual telescope

In 2017, scientists used a giant virtual telescope to create the first image of the black hole at the centre of our galaxy. They created the image by combining data from eight radio telescopes around the world, acting together as the Event Horizon Telescope (EHT), a virtual telescope that has the equivalent gathering power of a telescope the size of the Earth. The EHT's power is analogous to an optical telescope that would allow the reading of a newspaper on the Moon from the Earth. The black hole appears as a shadow against the thermal radiation of dust and gas that is being attracted by its intense gravitational field.

Einstein on black holes

Einstein disliked the notion of singularities (points of infinite gravitational field strength at the core of black holes) and argued that future models might do away with the need for the construct. In a paper in *Annals of Mathematics* in 1939, he concluded that: "The essential result of this investigation is a clear understanding as to why the 'Schwarzschild singularities' do not exist in physical reality." Einstein's intuition has not (yet) been proven right.

Windy black holes

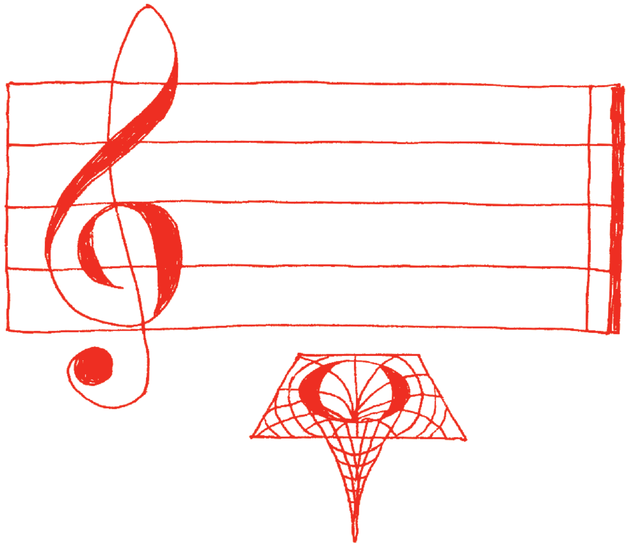
Scientists have observed incredibly strong 'winds' emanating from black holes. The ultra-fast outflows are emitted from the accretion disc of material that orbits a black hole and have been measured to reach velocities of up to a quarter of the speed of light. The flows absorb X-rays emitted from the black hole and are heated to millions of degrees.

The naked black hole

Supermassive black holes are typically found at the centre of galaxies. However, researchers have recently discovered a 'naked' (ie without a surrounding galaxy) black hole travelling at high velocity. The rogue black hole is moving at 2000 km/s, leaving a trail of debris in its wake. The lead researcher commented that they hadn't seen anything like this before and speculated that the black hole was ejected as the result of a collision between two galaxies.

Musical black holes

Observations made with NASA's Chandra X-ray Telescope have detected sound waves produced by a super massive black hole. The waves were found emanating from a black hole in the Perseus cluster of galaxies and are equivalent to a B flat which is 57 octaves below middle C. The waves are thought to originate from the collapse of cavities formed in the gas surrounding the black hole.



Stories from physics

Black holes' contribution to Wi-Fi

Though it might be felt that research into black holes is esoteric and brings few benefits to society, one significant tool has already been developed from their study. In the 1990s, John O'Sullivan was working with a team of researchers to detect radio signals from the mini black holes predicted by Stephen Hawking. To remove noise from pulses emitted from disturbed particles in the interstellar medium, the team developed an approach to signal analysis using a fast Fourier transform (an algorithm that changes the form of a signal). O'Sullivan realised the idea could be applied to the problem of communication between computers. Radio wave communication between computers was, at the time, difficult to achieve as waves reflected from nearby surfaces interfered with data transmission. His team realised that if data were sent over multiple frequencies and recombined by a fast Fourier transform, interference could be reduced. O'Sullivan's work is used in current Wi-Fi systems.

Water surprise!

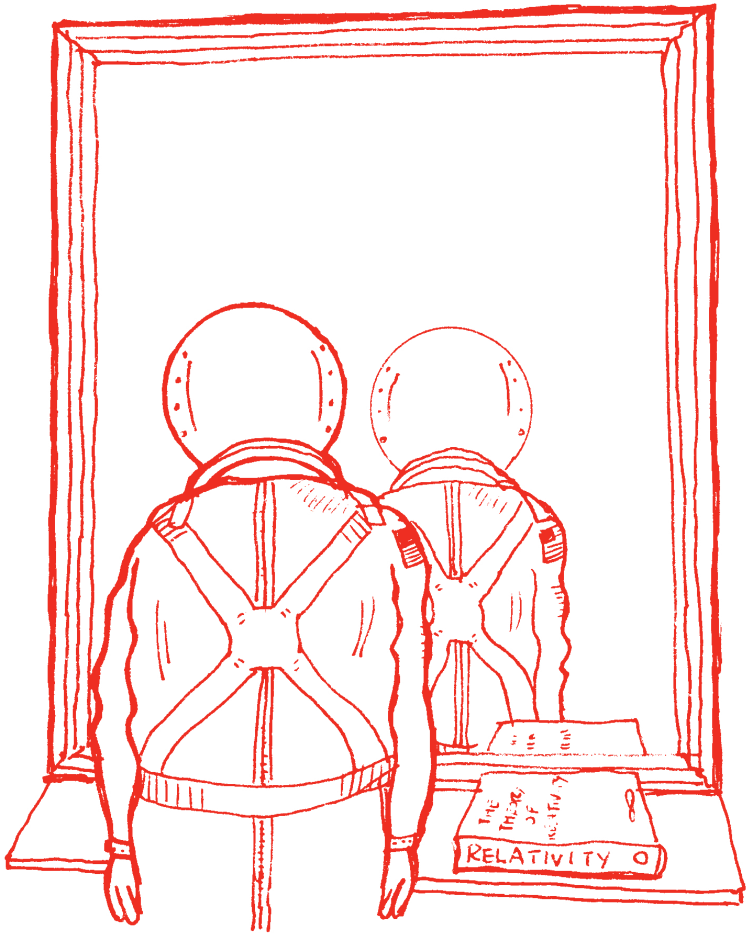
Astronomers have discovered the largest known reservoir of water in the universe in a quasar - a feeding supermassive black hole (ie one into which matter is being sucked). This quasar is formed of a black hole 20 billion times the mass of the Sun and emitting a thousand trillion times its radiation. The water vapour exists in a region around the black hole hundreds of light years in size and is heated to -53°C by energy from the quasar.

The collider panic

Following sensational media reports that the Large Hadron Collider (LHC) might produce a black hole when switched on, James Gillies, the head of public relations at CERN, had to field phone calls from tearful members of the public expressing fears for their children. The Nobel Prize winning physicist, Frank Wilczek, received death threats from people fearful about the consequences of the LHC's experiments. The CERN website reassured visitors that: "If micro black holes do appear in the collisions created by the LHC, they would disintegrate rapidly, in around 10^{27} seconds."

How to see the back of your own head

The *Schwarzschild radius* is the distance from the singularity of a black hole at which the escape velocity equals the speed of light. The *photon sphere* is an imaginary sphere of radius 1.5 times the Schwarzschild radius. Here, a horizontally aimed photon would go into orbit around the black hole and an astronaut, also in orbit at the same altitude, would be able to see the back of their own head by looking forwards.



A full set of references for this booklet is available at
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Dr Richard Brock

Lecturer in Science Education at King's College London.

After teaching physics in secondary schools for eight years, Richard studied for a PhD in physics education and now teaches and conducts research at King's College London.

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