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BLACK HOLES: THE END OF SPACE AND TIME

A Lecture by

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BLACK HOLES: THE END OF SPACE AND TIME

HEATHER COUPER

This lecture really ought to be called "Supernova - The Sequel", because it follows on faithfully from what I was saying last week. In particular, it looks at what's left after the event you might call "the moment of stardeath". Let's not get too gruesome, but I'm talking here about corpses and cadavers - of the celestial kind!

Before we see what's left after the supernova, let's look at the fate of normal stars like the Sun, which "snuffed it" by blowing off their outer layers as a planetary nebula. As befits its shape, a planetary nebula is a cosmic wreath. It marks the death of a star. Not only has the star expelled much of its matter to form the nebula - as gases and 'smoke' which will eventually dissipate into space - but its nuclear furnace is now switched off. The core that we see at the centre of the planetary nebula is not a star in the ordinary sense: it can produce no more energy. At first, the core is hot, with the remnants of heat generated at an earlier time, but it will now cool down, slowly but inexorably, as it radiates the stored heat to the cold depths of space. What was a mighty red giant degenerates into an insignificant 'white dwarf'.

As its name suggests, a white dwarf is a tiny object - no larger than planet Earth - but glowing white-hot from the heat stored within. Because of its small size, a white dwarf cannot help but be a dim object. Astronomers reckon that over 10,000 million stars in our Galaxy have already died, leaving white dwarf corpses. That means that there is at least one white dwarf for every ten ordinary stars in our Galaxy. But white dwarfs are so much fainter than ordinary stars that it is difficult to spot them. Among the thousands of stars we can see with the naked eye, none is a white dwarf: even the nearest white dwarfs appear so dim that you need a telescope to see them.

Astronomers came across white dwarfs in a roundabout way. In the 1830s, Friedrich Bessel was measuring the positions of stars that he suspected lay near the Earth, trying to detect a slight 'wobble' that would give away their distances. On Bessel's list was Sirius, the Dog Star, but it was not showing the 'wobble' that he expected - an apparent side-to-side motion every year that is caused by our changing viewpoint as the Earth moves around the Sun. Instead, Sirius was swinging back and forth much more slowly, taking decades to complete one swing.

There was only one answer. Sirius must have a companion star that we cannot see. This 'invisible star' and Sirius both follow orbits around their centre of gravity, which lies between them: it's like watching a dumbbell spinning end over end, with one weight (Sirius) painted white so we can see it and the other black and invisible. In 1844, Bessel boldly announced that he had 'discovered' a companion star to Sirius, even though he could not actually see it.

Bessel's logic was indeed correct. Almost two decades later, an American telescope maker, Alvan Clark, was testing his latest instrument - the world's most powerful refractor. Clark had to check the quality of the telescope's giant lens by looking at a bright star, so he set his son, Alvan Graham Clark, to watch through the telescope for Sirius' appearance from behind some nearby buildings. To the younger Clark's surprise, the star that rose from behind the building was only 1/10,000 as bright as Sirius. Before he could react, however, a dazzling star appeared right on its heels. The second star was Sirius itself: the dim star was the companion that Bessel had predicted. Because it keeps the Dog Star company, astronomers have nicknamed this fainter star 'the Pup'.

At first, no one was too surprised. After all, stars come in a whole range of brightnesses, and Sirius' companion could be a star that was quite cool and so gave off less light than white-hot Sirius. But, in 1914, the American astronomer Walter Adams managed to measure the temperature of the Pup for the first time. He found that it is every bit as hot as Sirius itself.

If the two stars were equally hot, how could they shine with such different brightnesses? The only answer was that the Pup was very much smaller that Sirius - only a little larger than a planet like the Earth. This, in itself, amazed astronomers, who up until then had thought that stars were always much bigger than planets.

But that was just the beginning. The orbit of Sirius and the Pup around each other provided a cosmic balance, which allowed astronomers to work out the amount of matter in the Pup. It turned out to be almost as heavy as the Sun. To fit this amount of matter into a body no larger than a planet, you have to squeeze it to a density far beyond anything we know on Earth. The densest metals, iridium and osmium, are twenty-two times denser than water. The material of the Pup has a density a million times higher than that of water. If we took a piece of white dwarf material the size of a sugar cube, it would weigh a tonne - or, in the words of an astronomer of the time: 'if we could pack our terrestrial goods as closely as these stars are packed, we could carry about one hundred tons of tobacco in a tobacco pouch, and several tons of coal in each waistcoat pocket.'

Now that we know the whole story of a star's life, the high density of a white dwarf is not so surprising. It consists of matter that has been through some of the worst experiences that Nature can contrive. This material was once the core of a star, forming a fierce nuclear reactor that destroyed millions of tonnes of matter every second. When the reactor ran out of fuel, the cruel hand of gravity crushed the core as tightly as it could, so tightly that atoms themselves could not stand the strain. In a white dwarf, atoms are broken up and their constituent parts - electrons and nuclei - are crushed together, to produce a density far higher than we can create on Earth.

Despite their faintness, astronomers have now found hundreds of white dwarfs. Some live on their own in space, but many are companions to ordinary stars. The brightest star in the Little Dog, Procyon, has its own 'pup' of a white dwarf. Like Sirius's Pup, Bessel predicted this companion in 1844, and it was only seen many decades later. It is, however, far from white-hot. With a temperature of 5000°C, it is cooler than our Sun and shines with an orange hue. Nevertheless, astronomers stick to the name white dwarf: now, however, it is a label for this kind of collapsed star, rather than a literal description.

In fact, every white dwarf will change in colour as time goes by. A white dwarf is a burnt-out corpse of a star, with no way of generating its own light and heat. It shines only because it once harboured fierce nuclear reactions. Once the reactor switches off, the white dwarf can do nothing but cool. Like the dying embers from a fire, the dwarf will fade from a brilliant white, to a glowing yellow-orange to a dull red cinder.

White dwarfs, with their enormously high densities and immense gravitational pull, are difficult things to imagine. Hardly anyone had thought that they would turn out to be small fry compared to some star corpses out there. And the discovery of this new breed of dead stars was almost as strange as the objects themselves.

It was Christmas of 1967. Like everyone else, most scientists were preparing for a well-deserved break: lights went out in the laboratories; long-running experiments were set to run automatically until the New Year.

But not in a Victorian building tucked down a narrow lane in the backstreets of Cambridge. At the Cavendish Laboratory, the lights were burning late into the night, as researchers pored over the latest results from their new radio telescope. This highly sensitive 'ear' on the heavens was picking up a quiet, regular 'ticking' from a point in the sky in the constellation Lacerta.

The Cambridge scientists were perplexed. Had they found an unexpected kind of natural cosmic clock? Or were they picking up the first signals from an alien intelligence? Only half in jest, they labelled the mysterious signal 'LGM1' - for 'little green men'.

Like many other discoveries, the Cambridge astronomers had stumbled across these signals from space when they were looking for something else. Since the end of the Second World War, they had been building bigger and better radio telescopes, to find out what objects in space are natural 'broadcasters' of radio waves. The Cambridge team had already found a 'hiss' of radio static coming from glowing nebulae, from the gases thrown out by supernovae, and from distant exploding galaxies.

Tony Hewish realized that the radiation we pick up from some galaxies should fluctuate quite wildly. This 'scintillation' is nothing to do with the galaxy itself, but arises when the radio waves, on their way to the Earth, pass through the turbulent wind of gases streaming out from the Sun's surface. It's a radio version of the twinkling of the stars that we see with our own eyes, as starlight passes through the Earth's turbulent atmosphere.

To measure this scintillation, Hewish needed a huge radio telescope - bigger even than the famous instrument at Jodrell Bank. So he settled on a novel design. The 'telescope' would simply consist of thousands of wires strung across the tops of wooden poles. In the summer of 1967, a keen bunch of students began to erect the new instrument: 1,000 wooden posts and 120 miles of wire, covering an area of ground as large as fifty-seven tennis courts. This 4½-acre field soon began to reap an unexpected crop of signals from space.

The person in day-to-day charge of Hewish's telescope was a young researcher, Jocelyn Bell. She immediately found that some galaxies were scintillating, as Hewish had predicted. But she also found some other fluctuating signals, which looked rather different. Bell was recording the radio signals on a paper chart that ran slowly under a moving pen, and the unexpected signals looked like 'scruff' on her charts.

Many researchers would have ignored the 'scruff'. But Hewish and Bell decided to take a closer look. They rigged up a faster chart recorder, which would show just how the radio signal was fluctuating. On 28 November, Bell watched in astonishment as the celestial signal activated the pen. As if driven by a clock, the pen jumped sideways and back, sideways and back, in a rhythm that was utterly regular, and steadier than Bell's own pulse. The period between each 'cosmic pulse' and the next was precisely 1.337 seconds.

Hewish, quite understandably, concluded that it was 'some man-made interference'. He asked around to find out if any scientist in Cambridge was operating equipment that pulsed at this unusual rate. But no one was. At the same time, other members of Hewish's team 'tuned' the telescope to a different wavelength, and found the pulses coming with the same rhythm, but all just a fraction of a second later. No man-made interference would come at different times at different wavelengths. But the gases in space would delay the longer radio wavelengths in precisely this fashion. This measurement told Bell and Hewish that the pulses had come a thousand light years from whatever - or whoever - was broadcasting them.

So, as Christmas approached, Hewish began to wonder if this 'pulsar' represented 'some message from extraterrestrial beings'. The whole Cambridge team began to discuss how they would break such news to the world. Bell, however, was in two minds about the possibility. She was trying to complete a programme of research into scintillation, 'and some silly lot of little green men had to choose my aerial to communicate with us!'

Hewish realized that 'little green men' had to live on a 'little green planet' that was going around a star. As the planet moved, the regular pulsing would change, by a tiny amount. He checked the pulses carefully, day by day - even interrupting Christmas lunch to make one vital measurement. By January, he was sure. The pulsar was not orbiting a star, so it was not an interstellar beacon on another world.

Bell, meantime, was ploughing her way through literally miles of paper chart that the telescope had produced over the months. She found three other pieces of 'scruff' - which turned out to be pulsars, too. They were in different parts of the sky, and their signals pulsed with a different beat. It was highly unlikely that four lots of aliens would be trying to signal to our planet Earth at the same time, and in a similar kind of way. Pulsars must be a natural constituent of the universe.

But what were they? No ordinary star could produce pulses as quickly and as regularly as the radio signals that Bell had found. There was only one answer: a neutron star.

A 'neutron star' is not really a star at all. A star is a large object, made of gases, which shines because of nuclear reactions deep within its heart. A neutron star is in many ways more like a small version of planet Earth. It has no nuclear furnace; it is only a few miles across; and it has a solid surface, or crust, that encloses a liquid interior.

But there the resemblance stops. While the Earth - and the other planets - is composed of ordinary atoms (such as iron, silicon and oxygen), a neutron star is made of tiny subatomic particles, called neutrons. You can pack neutrons together much more tightly than you can fit atoms together, so the matter in a neutron star is very compacted, and even denser than in white dwarfs. A pin head of matter from a neutron star would weigh a million tons!

With this fantastic degree of packing, a neutron star can contain a tremendous amount of matter. A typical neutron star is only fifteen miles across, but contains more matter than the Sun. This concentrated mass exerts an incredible gravitational pull - 100,000 million times stronger than the Earth's gravity.

The strong gravity means that human astronauts can never land on a neutron star. No rocket engine could slow a spaceship sufficiently to prevent a crash landing, and if an astronaut did try to stand on the neutron star's surface, its gravity would crush him or her to a layer of slime as thin as a film of oil on a wet pavement.

Suppose, for a moment though, that we could investigate the surface of a neutron star at first hand. We would notice it is very smooth. There may be some 'mountain ranges' or even 'volcanoes' (where molten neutrons erupt from below the solid crust), but the powerful gravity means that the Himalayas of a neutron star are no more than an inch high. For a mountaineer, however, they would represent more of a challenge than Mount Everest. In the battle to climb even an inch upwards against the neutron star's gravity, the mountaineer would have to expend more energy than the human body can produce in a lifetime.

Despite their problems in climbing upwards, travellers on a neutron star could use one familiar aid in navigating their way around the tiny world: a magnetic compass. Like the Earth, a neutron star has its own magnetic field, which breaks the surface at two 'magnetic poles'. A compass needle lines up with the direction of these poles. Navigators on the Earth always have one problem with a magnetic compass: the magnetic poles are not exactly at the North and South Poles of our planet, but lie a few hundred miles away, so a compass needle does not show true 'North-South'. Nonetheless, the correction on Earth is usually small. Not so on a neutron star. The magnetic poles can lie anywhere on the surface - even on the neutron star's equator - so compass directions would give you an entirely different map from ordinary lines of latitude and longitude.

In its magnetic field - as in its other properties - a neutron star takes things to extremes. A neutron star is the most powerful magnet we know in the Universe, with a magnetism a million million times stronger that the Earth's. And it was this intense magnetism that betrayed the existence of neutron stars to Jocelyn Bell and Tony Hewish.

The neutron stars in our Galaxy are so small, and so far away, that we could never expect to see one with either an ordinary telescope, or with a radio telescope. But the powerful magnetic field changes these ground rules. It traps electrons in the nearly empty space near the neutron star, and whirls them round and round. The captive electrons respond with a cosmic scream for help - a powerful beam of radio waves broadcast out into space from each of its magnetic poles. As the neutron star spins round, these twin radio beams sweep around, like the beams of light from the rotating lantern in a lighthouse.

A passenger on a cruise ship sees a distant lighthouse at night only as a series of flashes, regularly recurring as the lighthouse lantern rotates. Hewish and Bell were in exactly the same boat, cosmically speaking. The beams of radio waves from a distant neutron star were sweeping past them regularly as the neutron star rotated, so the radio telescope picked up a series of regular 'pulses'.

Generally, only one of a neutron star's two beams will sweep past the Earth, so the time between the pulses tells us how long it takes for the neutron star to spin round once. In the case of the first pulsar, this was a mere 1.337 seconds. This is about the same rate as the turntable on a record player, although here we are talking about something that is not just a few inches across, but some fifteen miles in diameter, and containing more matter than the Sun!

Even this incredible rate of spin has turned out to be on the slow side for neutron stars. Astronomers have now found over 400 pulsars, and most have periods of less than one second. The record-breaker turned up in 1982: it is a neutron star turning over 600 times in a single second! If we turned the radio pulses into sound, we would not hear this pulsar's signals as individual 'ticks'. They are so rapid that they would produce a musical tone - at the 'E' an octave and a bit above middle C.

Ordinary matter must be subjected to some pretty drastic treatment to reduce it to the state that we find in a neutron star. There is only one furnace we know that can forge a neutron star: the cataclysm of a supernova explosion.

As I described in my last lecture, an overweight star dies as a Type 2 supernova. Its small central core - made of iron - collapses suddenly, in a burst of neutrinos, and the outer part of the star explodes into space. In the last chapter we followed the fate of the exploding fireball; now let's see what happens to the star's collapsing iron core.

Like other everyday substances, iron is made of three kinds of subatomic particles: electrons, protons and neutrons. Electrons are the lightest of these, but - like marshmallows - they are comparatively large for their weight. In the shrinking core, they come off worst. The electrons are forced to amalgamate with protons, to become neutrons. So all the matter in the core ends up in the form of neutrons. Although these particles are very small, they have a definite size. Eventually, they are packed together, shoulder to shoulder, and gravity can squeeze them no closer. The core suddenly stops collapsing. It has become a neutron star.

The idea that supernovae can produce neutron stars had been around since the 1930s, but only when astronomers could detect neutron stars - as pulsars - could they check out the theory. Radio astronomers knew of hundreds of gaseous 'remnants' - the exploded remains of old supernovae. Now they began to look for tell-tale pulses coming from the centres of these remnants.

Top of the hit-list was the Crab Nebula. In July 1054, Chinese astronomers had witnessed its birth, in a 'guest star' so brilliant that they could see it even in daylight. This supernova gradually faded, disappearing from sight in April 1056. Unseen by astronomers on Earth, its gases were rushing outwards into space, forming a large egg-shaped nebula.

Early in the eighteenth century, an English astronomer first saw the glowing cloud of gas, just above the star that marks the lower 'horn' of Taurus, the Bull. In 1758, a French astronomer stumbled across the nebula again, while following a comet. Charles Messier - known as 'the ferret of comets' - described it as a 'whitish light, elongated like the flame of a taper'. With a more powerful telescope, a nineteenth-century astronomer, the third Earl of Rosse, could make out some wisps of gas in the nebula. He described them as 'claw-like appendages'; and the nebula has been known ever since as the 'Crab'.

Although the Crab supernova exploded over nine centuries ago, it was still one of the most recent nearby supernovae in our Galaxy. And so the Crab Nebula was a good place to look for a newly-born pulsar. Within months of Bell and Hewish announcing their first four pulsars, a team of American radio astronomers picked up the frantic beating of the Crab Nebula's heart: radio pulses streaming out at a rate of over thirty per second.

The young Crab Pulsar is one of the fastest, and brightest, that we know. Not content with generating just radio waves, its magnetic poles send out beams of more energetic radiations: gamma rays, X-rays - and light. In 1969, astronomers in Arizona looked carefully at a 'star' in the centre of the Crab Nebula. Their equipment showed it was not a steadily shining star at all: the object was flashing thirty times a second. The team had inadvertently left a tape recorder running, and it faithfully recorded their amazed reaction: 'it's bloody pulsing!!'

The Crab Pulsar is like the flywheel in an electrical generator. Its powerful magnetism threads its way through the surrounding nebula, stirring up the electrons to make the Crab Nebula glow as brightly as 100,000 Suns. But this feat drains energy from the spinning pulsar. As a result it is gradually slowing down. Over the centuries, the Crab Pulsar will rotate more and more slowly, its brilliant output of radiation fading gradually from sight.

In the southern skies, astronomers have found an older cousin of the Crab. In Greek myth, the constellation Vela represented the sails of the great ship Argo that carried Jason in quest of the Golden Fleece. Modern telescopes show that Vela does indeed display great glowing sheets - not of sailcloth but of gases erupted by a supernova some 11,000 years ago. Tucked in amongst the sheets is a pulsar, spinning thirteen times every second.

Radio astronomers were the first to pick up the Vela Pulsar. In 1977, astronomers used the great Anglo-Australian Telescope and electronic detectors to look for light from this pulsar - and picked up the faint flashes, right at the limit of detection. It is one of the faintest stars ever found, at magnitude 24 in the astronomers' brightness scale.

The other pulsars in the sky are older, and weaker, and astronomers can only pick them up by their radio broadcasts. After ten million years or so, even the radio emission becomes erratic. A pulsar stutters for a while; then it falls silent. Our Galaxy must be awash with millions of these silent pulsars - the undetectable neutron star corpses of supernovae that exploded in the distant past.

Neutron stars, however, are still not the ultimate star-corpse. To discover how a truly massive, energetic star can end its life, we have to go back more than 200 years - and across the English Channel.

The 1790s were revolutionary years in France. In 1789, the people of Paris stormed the Bastille. As the new decade unfolded, Louis XVI and Marie Antoinette were led to the guillotine, thousands of Parisians died in the 'Reign of Terror', and the country's rising star - Napoleon Bonaparte - led French troops in assaults on neighbouring countries that threw the whole of Europe into war.

Behind these traumatic scenes, another revolution was shaping up. A French scientist came to realize that gravity could become an irresistible force, a power so mighty that it could overwhelm even a speeding ray of light. When later mathematicians worked these ideas out in detail, they realized that our Universe could contain objects so bizarre that they would revolutionize our ideas about space, time and the Universe at large. These 'black holes' may control the eventual destiny of our Universe; they may act as time machines that could whirl a spaceship back into the past; they may form bridges through which our descendants can fly to *other* universes, entirely different from our own.

Pierre Simon de Laplace had no idea that he was pioneering so sweeping a revolution. A self-made man, he achieved his joint ambitions by becoming both France's leading scientist (after the guillotine had claimed the chemist Antoine Lavoisier), and a leading man of affairs (a minister of state and senator under Napoleon, he was later made a Marquis by

Louis XVIII). His main scientific work was in calculating the effects of gravity in the Universe.

In the previous century, Isaac Newton had concluded that every body in the Universe produces a 'pull' of gravity - identical to the force that keeps us firmly anchored to the Earth, and makes an apple fall from a tree. The Earth's gravity keeps the Moon in orbit around our planet; while the gravity of the mighty Sun forces the Earth to pursue its yearly path around our life-giving local star.

Laplace began to work out how strong the pull of gravity would be if we stood on different objects in the heavens. A body's gravity depends on the amount of matter it contains. So anyone who stands on our diminutive Moon would feel only one-sixth the usual pull of gravity - as the Apollo astronauts have experienced. If we could stand on the sun, gravity would be much stronger than we feel on the Earth.

Where gravity is stronger, it's also more difficult for us to get away. To propel a rocket from the Earth's surface out into space, we have to provide powerful engines that can accelerate it to a speed of 7 miles per second - 25,000 miles per hour. The Apollo astronauts leaving the Moon had to travel at only 1½ miles per second. At the other extreme, a hypothetical rocket would have to fly at a rate of 380 miles per second to break free from the Sun's gravity.

Laplace realized that heavier stars would have stronger gravity still. He calculated that a star 100 million times heavier than the Sun would exert a pull so strong that you would need to travel at 186,000 miles per second to escape. What's so special about this speed? It happens to be the speed of light. So the rays of light pouring from this brilliant star's surface would never get away into space. The star's gravity would bend the rays round and they would fall back on to the star's surface. A distant astronomer looking in this direction would see no light at all - and would have no idea that a supermassive star lurked there, unseen.

'It is therefore possible,' Laplace concluded, 'that the largest luminous bodies in the Universe may be invisible.' Astronomers of his time were not particularly impressed. Even if they accepted the apparent paradox that a 'luminous' object could be 'invisible', thanks to gravity, they had no way of finding these objects anyway.

But the seed was sown. In the twentieth century, astronomers began to realize the role that gravity plays in forming stars, in making them shine, and in causing the 'core collapse' that marks their demise. It became apparent that gravity is the unseen power behind the throne, both the starmaker and the starbreaker. Gravity, however, kept its ultimate power well hidden. As astronomers came to understand stars better, they realized that nature does not produce stars as massive as Laplace had envisaged. If the gases in a nebula begin to clump into such an object, the immense heat generated inside it breaks the gas clump up into smaller fragments - a cluster of protostars. The heaviest stars are around one hundred Suns in mass, rather than 100 million.

The power of gravity is, however, increased when you make an object smaller and denser. If we could shrink the Earth down to the size of a large marble, its gravity would be strong enough to prevent light from escaping. Fortunately, such a fate will never overtake our planet. But the death throes of a star do produce ultra-compressed corpses, with correspondingly powerful gravity. When the Sun dies, its core will shrink to become a white dwarf, which will be the same size as the Earth, but containing 200,000 times as much matter. To escape from a white dwarf, you need to travel at 4000 miles per second.

Even smaller and denser are the neutron stars - the ultra-compressed corpses forged in the explosion of a supernova. We have already discussed some of the effects of a neutron star's immense gravitational pull. Since it would take more than a lifetime's effort to climb a one-inch mountain on a neutron star, it's no surprise to find that you would need to travel at 60,000 miles per second to escape its gravity altogether. That escape velocity is one-third the speed of light. Clearly, neutron stars bring us close to Laplace's idea of an 'invisible body' - not a supermassive star, in fact, but a supercompressed star.

When Tony Hewish and Jocelyn Bell discovered neutron stars in 1967, astronomers quickly scented fresh game: a star-core so compressed that its gravity prevents light from escaping. Other scientists provided clues that encouraged the quest. In particular, a neutron star has a natural weight limit. As astronomers had found with white dwarfs, a heavier neutron star is *smaller* than a lightweight neutron star. If a neutron star were heavy enough, it would shrink to a point of no size at all. This weight limit is equal to the mass of three Suns.

When a heavy star explodes as a supernova, it blows most of its matter off into space. Only the small core collapses inwards. But astronomers know of stars so massive that even this 'small core' weighs more than three Suns. What happens when this core collapses? It is too heavy to become a white dwarf; it also exceeds the weight limit for a neutron star, so it has no option but to continue contracting, past the point where its gravity prevents light from escaping.

By the late 1960s, then, theoretical astronomers had convinced themselves that 'invisible stars' did exist, and American physicist John Wheeler provided a name that summed it all up: 'a black hole'. A supercollapsed star core is 'black', because no light can escape from its powerful gravity. It's gravity also forms the ultimate 'hole' in space. Anything can fall into a black hole - indeed, its strong gravity is a vacuum cleaner for anything cluttering space around it - but nothing can come out again. The reason is simple. Nothing can travel faster than light, so if light cannot escape, nothing else has a chance. Black holes are the graveyards of the Universe: places where matter disappears from sight, and can never return.

No one had yet found a black hole, but that did not stop the mathematicians from having a field day working out what happens in, on and around a black hole. Laplace had used Newton's law of gravity; mathematicians in this century have a better theory of gravity, Albert Einstein's 'General Theory of Relativity'. Einstein found that gravity is not just a force: it can change the nature of empty space, and slow the passage of time. In a black hole, gravity takes things to extremes.

For a start, the matter that made up the original star's core cannot withstand the inpull of its gravity. It shrinks to literally zero size - an infinitesimal point, where matter is crammed to an infinite density. This 'singularity' lies at the heart of the black hole.

The black hole itself is not an object. It is a region, a few miles across, that surrounds the singularity. Within this empty region, gravity is so strong that nothing can escape. Apart from its central singularity, a black hole must be empty. Once something strays inside it, the irresistible gravity pulls it down to the centre, and crushes it into the singularity, within a few millionths of a second.

Black holes are a very uniform breed. Because they show no distinguishing features, it's difficult to tell one from another. An astronomer who could approach a black hole (not too closely!) could tell how much matter it contained by measuring the strength of its gravity at different distances. He could also find if the hole has a magnetic field, or an electric field. And, if the original core was spinning around, this rotation will be impressed into the gravitational field, and so the black hole will drag the spaceship around, as well as pulling it in. But these three properties (mass, electromagnetic field, rotation) are not really enough to distinguish one black hole from another. Imagine trying to work out which friend someone is talking about if you were told only his/her weight, height and eye colour. Because of their lack of distinguishing marks mathematicians say 'Black holes have no hair'!

Although we can never see what's inside a black hole, mathematicians can tell us what it *ought* to be like inside. If the black hole is not rotating, then there's just the singularity at the centre, and anything falling in is irresistible crushed into the singularity. But the black holes we are likely to find in the Universe won't be like that. Everything we know in the Universe is spinning, from our own Earth, once a day, to the Milky Way Galaxy that turns once in 200 million years. When a star's core collapses to become a neutron star, it can end up spinning at a rate of several hundred revolutions every second. A black hole, formed from a shrinking star core, should rotate at a similar breakneck pace.

An Australian mathematician, Roy Kerr, has calculated that the interior of a spinning black hole is a fascinating place. Once again, all the matter of the original star core has shrunk into a central singularity which has an infinitely high density. Instead of being a point, however, the singularity is in the shape of a circular ring. Kerr finds that this ring-shaped singularity has an even odder property. Its rotation tends to cancel out some of the gravitational pull near the singularity. As a result, this singularity does not pull things inexorable inwards. In theory, if you fell into a rotating black hole, you could fly your spaceship all around - and even through - the singularity in the middle. If you came close enough to the singularity, you would find it did not attract your spacecraft, but repelled it instead. According to some calculations, you could fall into a rotating black hole, bounce off the singularity, and emerge again. But into a new universe, not ours.

The more bizarre the properties that mathematicians ascribed to black holes, the more preposterous it seemed that such objects *really* existed in our Universe. As late as 1970, a delegate to an international conference of astronomers wrote on the blackboard 'black hole = naughty word'!

The time was certainly over-ripe for astronomers to search for black holes in the Universe. But how? A black hole is, of course, completely dark, and we see it against the blackness of space. A black hole search is the celestial equivalent of looking for a black cat in a coal cellar on a dark night. There is, however, one easy way of locating your cat: arrange an altercation with another cat, and home in on the resulting fracas!

For astronomers, the 'other cat' is an ordinary star, which happens to be a companion to a black hole. The squabble is over the outer layers of gas making up the companion star. The black hole drags this gas from the ordinary star. As the gas falls towards the black hole, it becomes hotter and hotter. Eventually - just before it disappears inside the black hole - the tormented gas radiates away vast amounts of energy, not as light or radio waves, but in the form of X-rays.

So 'X-ray astronomy' was the key to the search for black holes. Unfortunately, X-rays from space don't make it down to the Earth's surface. After an epic journey of thousands or millions of light years, these rays are stopped by the thin layer of air above our heads.

So it was that, on 12 December 1970, American scientists launched a revolutionary satellite to scan the Universe for X-rays. The launch site was Kenya, and the date the seventh anniversary of the country's independence; so the satellite was christened 'Uhuru' - Swahili for 'freedom'.

Uhuru found dozens of star-pairs in our Galaxy which were powerful emitters of X-rays. But these X-ray sources were not necessarily the work of a black hole. A neutron star has sufficiently strong gravity to rip gases from a companion star, and heat the infalling gas until it emits X-rays. Indeed, some of Uhuru's X-ray sources gave themselves away immediately as neutron stars. Just as Bell and Hewish had picked up an uncannily regular 'pulse' of radio signals from spinning neutron stars, so Uhuru found that some of its sources were sending out regular flashes of X-rays.

Out in the constellation Cygnus, however, Uhuru found an X-ray source that did not flash or pulse, and which might be the work of a black hole. But astronomers are conservative people. They don't like to admit an unknown creature to the cosmic menagerie unless they are absolutely sure it exists, especially if it's a beast as exotic as a black hole.

Fortunately, ordinary telescopes showed astronomers the normal star that is the victim in the Cygnus X-1 system. It is a hot, blue giant star - type B in the Harvard system - which means it weighs as much as twenty Suns. Astronomers can study how it's moving, by breaking its light into a spectrum and investigating how the dark lines in the spectrum change as this star and its unseen companion endlessly circle one another, once every six days. The swing of these two objects around their centre of gravity acts as a giant cosmic balance, allowing astronomers to compare their masses. The unseen companion weighs in at exactly half the mass of the star we see - in other words, at ten suns. This is way above the weight limit for neutron stars (three suns), so the voracious object in the Cygnus X-1 system must be a black hole.

Not many black holes will be so well placed,. snuggled close up to an easily visible companion, so it's not too surprising that astronomers have found only a few more black holes since their success with Cygnus X-1 in the early 1970s. But each discovery bolsters the theory that heavy stars do leave black hole corpses.

Black holes - understandably - have a reputation for doom and destruction. But the supermassive stars that generate them seem to be blessed with a more philanthropic streak. Let's turn the clock back to the supernova in which the black hole was born - and in particular, to the aftermath of the outburst itself. The fires of the original explosion have long since faded from sight, but the debris from the supernova has been shooting out at tremendous speeds.

It hasn't been rushing out into a vacuum, however. The space between the stars is filled with gas - albeit very tenuous - and the debris from the supernova has cannoned into it. The high speed collision has created a 'supernova remnant', which is so brilliant when viewed with a radio telescope or an X-ray satellite.

It's a safe bet that the larger and fainter sources detected by these telescopes are the remains of supernovae that exploded in the more remote past, before even the Chinese were keeping records. Astronomers therefore have a picture gallery of these supernova remnants of all ages. And with the older remnants, a surprising picture begins to emerge.

Some 100,000 years after a supernova's explosion, its expanding gases have swept up a vast amount of interstellar gas - far more than the supernova itself threw out. Like the frozen debris in front of a snowplough, this gas is squeezed into thin sheets, or filaments, in space. Once something has squeezed the gas in space together, its own gravity takes over, drawing the gas in closer and closer, tighter and tighter, until a new cluster of stars is born.

Indeed, astronomers have found young stars sprinkled around the edges of some very old supernova remnants. So one supernova can compress enough gas to spawn a whole bunch of new stars. A supernova is a phoenix: from its ashes rise a whole new generation of stars.

But its legacy doesn't end there. The alchemical furnace in the dying star forges all kinds of new elements - up to iron - from the star's original supply of the lightest element, hydrogen. The raging inferno of the explosion itself can transmute some of the iron into even heavier elements: uranium, lead copper, silver, gold. These are rare - and hence valuable - elements on the Earth, and in the Universe at large, because they are forged only in the most exotic of all locations, the heart of an exploding star.

The explosion throws all these substances out into space, to 'enrich' the gas in our Galaxy with heavy elements. Astronomers now believe that our Universe originally consisted of only the two simplest substances - hydrogen and helium. All the other elements were built up within stars - some step by step over millions of years, others in the tumult of a supernova explosion.

Without supernovae, then, we would lack gold, silver and platinum - the finer things of life. But we would also lack life itself. Other stars may eject carbon and nitrogen into space, but only supernovae can produce the iron and silicon that make up the bulk of our planet. And elements like iron and calcium - the by-products of a supernova - are essential to the running of living cells. Without them, our bodies (and those of other living things) could not function. It is no exaggeration to conclude that we are, indeed, made of stardust.