# Black hole blues

For a century, scientists have tried to solve the riddles posed by Einstein's theory of relativity

**By Marcus Chown**

In February 1916, Albert Einstein received a surprising package. It came from a soldier serving on the eastern front. Karl Schwarzschild had been the director of the Astrophysical Observatory in Potsdam, just outside Berlin. However, at the outbreak of war in 1914, he had been overcome by patriotic fervour, dropping everything to volunteer for military service. In his 18 months in the Kaiser's army, he had run a weather station in Belgium, calculated shell trajectories with an artillery battery in France, and now he was serving in Russia.

Despite being in the midst of a war, Schwarzschild wrote several scientific papers, two of which were on Einstein's theory of gravity, which he had learned about soon after its publication at the end of 1915. What was surprising about Schwarzschild's work was that in such a short time he had taken a significant step beyond Einstein.

Einstein had discovered that mass warps space-time, and that warped space-time is gravity. "Matter tells space-time how to curve. And curved space-time tells matter how to move." This, as the summary goes, is Einstein's theory; the general theory of relativity.

Because of the complexity of Einstein's equations it is very hard to deduce the shape of the space-time in the vicinity of a realistic body. Schwarzschild, however, had made a number of simplifying assumptions, which reduced the equations to a more manageable form, and enabled him to "solve" them.

Schwarzschild's self-declared solution described the shape of the warped space-time in the neighbourhood of a localised mass such as a star. Einstein was amazed. "I had not expected that one could formulate the exact solution of the problem in such a simple way," he wrote back to Schwarzschild.

Most remarkably, Schwarzschild showed that, if enough mass was crammed into a small enough volume, space-time would become so warped as to become a bottomless well. So steep would be its sides that a light beam trying to climb out would die of exhaustion, sapped of all its energy, before it could escape. With no light emerging from the region of space-time, it would appear blacker than night.

Schwarzschild had no word for what he had discovered. The term would only be invented by the American physi-

*A young Albert Einstein (date unknown)*

ANN RONAN PICTURES/PRINT COLLECTOR/GETTY IMAGES

cist John Wheeler in 1967. Today, however, there is hardly a person alive who does not know it: a black hole.

The black hole was surrounded by an imaginary membrane, now called an "event horizon". Anything passing through it – whether light or matter – could never get out again. If a star was crushed by its own gravity to within its event horizon, its gravity would continue to crush the star all the way down to an infinitesimal point.

At the centre of the black hole, where the matter of a star is crushed to infinite density, the curvature of space-time and the strength of gravity sky-rocket to infinity. "Black holes are where God divided by zero," said the American actor and writer Stephen Wright. The appearance of such a nonsensical "singularity" in any theory indicates that it no longer describes reality. It has broken down. "If this result were real, it would be a true disaster," said Einstein.

Not for an instant did Einstein think the result was real. And nor did Schwarzschild. And neither man entertained the thought that the black hole solution described an object that might actually exist in the universe.

Those astronomers who did were not overly worried either. A star has a finite supply of energy and, when it exhausts it, its internal fires must go out. Since those fires push outwards and prevent gravity from crushing the star during its lifetime, the star will begin shrinking. But it was inconceivable that nature would permit the formation of a monstrous singularity. Some new force was bound to come to the rescue and halt the shrinkage long before that happened. And indeed it appeared nature provided just such a force. It was a consequence of the bizarre theory of the microscopic world of atoms and their constituents.

What we know as "quantum theory" was stumbled on in the first decades of the 20th century but given a firm mathematical foundation only in the mid-1920s. It recognised that the fundamental building blocks of matter behave as both localised particles and spread-out waves. This peculiar "wave-particle duality" leads to a multitude of strange phenomena – for instance, the ability of a single particle to be in two places at once. It also plays a crucial role when a star at the end of its life runs out of the fuel necessary to maintain its internal fires.

Robbed of its ability to push outwards, the matter of a star is crushed by gravity until it fills a volume of about the size of the Earth. Such a "white dwarf", 100 times smaller and about a million times denser than the Sun, is the end-point of the evolution of all normal stars, including our own. In such super-dense conditions – a sugar-cubed-sized volume of white dwarf stuff weighs as much as a family car – the electrons are forced very close together.

Squeezing a wave of any type into a small space makes it more choppy and violent. In the case of a quantum wave, more choppy and violent corresponds to a faster moving particle. This is the famous "Heisenberg uncertainty principle". It dictates that, when electrons are squeezed tightly together inside a white dwarf, they attain extremely high speeds.

But this is not the only quantum effect with important implications for white dwarfs. Another, more difficult to explain consequence of wave-particle duality is that the fundamental building blocks of matter come in two distinct tribes: "bosons", which are gregarious and "fermions", which are antisocial.

Fermions, which include the electron, obey the "Pauli exclusion principle", which states that no two fermions can occupy the same quantum "state". For electrons in a white dwarf this means two neighbouring particles must have distinctly different velocities. So, if one has a velocity dictated by the Heisenberg uncertainty principle, its neighbour must have an even higher velocity.

Imagine a ladder, with each rung corresponding to a higher and higher velocity. According to the Pauli exclusion principle, there can be only one electron on each rung (actually, it's two, but that's another story). It therefore ensures the electrons in a white dwarf have extraordinarily high velocities, boosted way beyond what the Heisenberg uncertainty principle might suggest. And it is these super-fast electrons buzzing about inside the stars that push back against gravity. Their so-called electron degeneracy pressure keeps a white dwarf stable and prevents it from shrinking to a ball much smaller than the Earth.

*Quantum theory came to the rescue of a dying star*

So, in the late 1920s, it was believed that quantum theory came to the rescue of a dying star. It staved off the runaway collapse down to a black hole with a nightmarish singularity in its heart. All was under control. Everything in the garden was rosy – or so it seemed.

In August 1930, a 19-year-old Indian mathematical prodigy called Subrahmanyan Chandrasekhar embarked on a ship in Bombay bound for England. The voyage was initially assailed by bad weather and the ship had to steam at half-speed; as they passed Aden, the sun came out. And, as the ship made its way through the Suez Canal, Chandrasekhar at last was able to leave his cabin, where he had been imprisoned during the heavy seas. Sitting on deck, he at last had the time to think. And what he thought about was white dwarfs.

One question occupied Chandrasekhar's mind: how fast were the electrons in a white dwarf moving? Flicking back and forth between his books and papers, he gathered the formulae that described the interiors of stars and the quantum behaviour of electrons at ultra-high density. He put in the numbers and cranked away until there emerged an answer. Inside a white dwarf, he discovered, the electrons would be moving at more than half the speed of light.

Such velocities were staggeringly huge: more than 150,000 kilometres per second. But more important to Chandrasekhar was the implication of such speeds. It meant that quantum theory alone was insufficient to understand white dwarfs. A correct theory must also incorporate Einstein's special theory of relativity, which describes motion near the speed of light.

It did not take long for Chandrasekhar to develop a properly "relativistic" theory of white dwarfs. And it did not take long for him to discover something unexpected, if not horrifying.

The more massive a white dwarf, the more its gravity squeezed the electrons in its interior and the faster they buzzed about. Except that Einstein's theory of relativity imposed a limit on how fast the electrons could go: the speed of light. As the electrons approached the cosmic speed limit, they became ever more massive and it became ever harder to boost their speed. But this created a problem. After all, it was the continual drumming of the electrons – like raindrops on a tin roof – that provided the outward force to oppose gravity. If electrons were squeezed harder and harder, their speeds were boosted by ever smaller amounts and their ability to oppose gravity was sapped away. The young Indian saw it like a train bearing down on him in the night: a looming stellar catastrophe. For a white dwarf, the stiffness of the electron gas holding back gravity was like the stiffness of a cricket ball resisting a bowler's grip. But, above a certain stellar mass, everything changed. The cricket ball turned to marshmallow.

Chandrasekhar redid the calculation, over and over. There could be no doubt. If a star at the end of its life were more massive than 1.44 times the mass of the Sun, electron degeneracy pressure would not be enough to save it. Gravity would crush the star catastrophically. No known force in the universe could stop it. The monstrous singularity was unavoidable.

Two years later, in 1932, the English physicist James Chadwick found a particle as massive as the positively charged proton, but with no electric charge. With the discovery of the "neutron", the picture of the atom was complete: negatively charged electrons orbit a compact "nucleus" which contains protons and neutrons (the exception being an atom of the lightest element, hydrogen, whose nucleus contains a lone proton).

Chadwick's discovery had crucial implications for a star more massive than the "Chandrasekhar limit" of 1.44 solar masses. Yes, its innards would be turned to marshmallow and it would be crushed ever smaller by the grip of gravity. But this was not the whole story. The runaway shrinkage of the star would, inevitably, squeeze the electrons into the nuclei, where they would react with the protons to make neutrons.

*The monstrous singularity was unavoidable*

Neutrons, like electrons, are fermions. And a neutron gas, just like an electron gas, would make the star stiff enough to resist gravity. Neutrons, however, are much smaller than atoms. Instead of a white dwarf the size of the Earth, the result would be a ball of neutrons the size of Mount Everest. So dense would be such a "neutron star" that a sugar cube-sized volume would weigh as much as the entire human race.

Although "neutron degeneracy pressure" makes neutron stars stable against further gravitational collapse, they have the same achilles heel as white dwarfs. Their constituent particles are flying about at close to the speed of light. Consequently, above a certain threshold of mass, even the stuff of a neutron star turns to marshmallow.

The physics of neutrons is more complicated than the physics of electrons. Consequently, the threshold mass for a neutron star is not known as precisely as the Chandrasekhar limit. But it is widely believed to be about three times the mass of the Sun. For stars heavier than this, there is no known force that can stop their shrinkage to form a black hole.

This mass limit would not matter if there are no stars heavier than three times the mass of the Sun. But some stars are many tens of times as massive as the Sun. Such stars are prone to violent convulsions that eject large quantities of their mass. However, even taking this into consideration, they are still likely to be more massive than three solar masses when their internal fires finally flicker and go out. Runaway collapse to form a black hole appears unavoidable.

Yet all hope was not lost for Einstein's theory. Its singularities might not be inevitable. One way out remained. A singularity is inevitable if the collapse of a massive star is perfectly spherical. Stars are not perfectly spherical, however.

Depending on how fast they rotate, their waistlines bulge outwards. And any unevenness like this will be magnified, as the star is crushed ever smaller by gravity. It means that different parts of the collapsing star may not pile up at one impossibly dense point. They may miss each other. The singularity will be avoided and Einstein's theory of gravity will survive intact.

Enter English theorists Roger Penrose and Stephen Hawking. Between 1965 and 1970, they proved several powerful "singularity theorems" not only about the singularity in a black hole but about a second type of singularity in the big bang in which the universe was born 13.82 billion years ago. The most important of them showed that, under a wide range of general and highly plausible conditions, the singularities were unavoidable.

There was no escaping the truth. Einstein's theory of gravity contains the seeds of its own destruction. Despite its stunning successes, it also predicts nonsensical singularities. It breaks down in the heart of black holes and at the beginning of time. It can only be an approximation of a better, deeper theory. Only a knowledge of this deeper theory of gravity will tell us what really happens at the heart of black holes and, most importantly, shed light on the origin of the universe in the big bang.

All other fundamental forces in nature are described by quantum theory. The theory is hugely successful. It has given us lasers and computers and nuclear reactors. It explains why the Sun shines and why the ground beneath our feet is solid. The best bet of physicists is, therefore, that the deeper theory of gravity is a "quantum theory of gravity".

At the moment, although there are promising avenues, physicists are stumped. A century after general relativity, we may need another Einstein to shed light on what gravity, space and time really are. "Gravity", in the words of Frank Cottrell Boyce, "is not a trivial monster." ●