# Black Holes and Bangs

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Yesterday, just after 3 in the morning, I was fast asleep. I slept through the moment the Earth was shaken by a disturbance in spacetime, a ripple in the Universe's fabric which passed, briefly, across our planet, stretching and compressing everything familiar as it went. The disturbance lasted only a fraction of a second, and, as the displacement was tiny, it was largely unnoticed. Certainly, you won't have felt anything, even if you were awake, and were it not for the presence of four highly sensitive detectors – in Japan, Italy, and the Us, in Louisiana and Washington state – we would have been collectively completely oblivious to the passage of this gravitational wave, the product of an unimaginably violent collision which took place hundreds of millions of years ago, hundreds of millions of light-years away. Far from sailing smoothly through the cosmos, the discovery of such events forces us to think of our Earth – and ourselves – travelling through a choppy spacetime sea.

On August 17th, 2017, the orbiting Fermi observatory caught a flash of light coming from a spot in the northern sky. Fermi is sensitive to gamma-rays, the highest energy light, and the burst it saw lasted only two seconds. However, other telescopes joined the fray and eleven hours later a new star, a supernova[1], was seen in the otherwise nondescript galaxy NGC4993, 140 million light-years from Earth. Meanwhile, those gravitational wave observatories – and LIGO, the observatory which consists of the two US detectors – had also recorded a disturbance in space, only the sixth to ever be confidently detected. This time, the disturbance was long lived, lasting for more than a minute, but it seemed to coincide with the flash of light seen by Fermi and another gamma-ray observatory, INTEGRAL.

This was the first time that we had seen both a gravitational wave and an electromagnetic signal, and it was a big deal. Though technically secret until the first papers describing the event were published, it seemed for a while like every astronomer on the planet was involved in following up this fascinating object, now known as GW170817. In the end, more than seventy observatories added observations to a pile that revealed that the event was caused by the collision of two neutron stars, the immensely dense remnants of the cores of massive stars which had themselves gone supernova millions or billions of years ago. Spiraling inward, and then colliding, the immense amount of energy released not only produced the gravitational wave and light we saw, coupled with the density of material caught up in the event it drove nuclear fusion reactions capable of producing heavy elements; if you are wearing any gold jewelry, we now know that it was forged in events such as this one. The Universe's most violent events produce beautiful results.

Let's step back. Gravitational waves, those ripples in space, are a prediction and a consequence of Einstein's theory of relativity, which explains gravity as the distortion of space[2] by mass. The Earth orbits the Sun because the Sun's gravity distorts space around it – think of sci-fi words such as 'gravity well', or all those demonstrations involving bending rubber sheets. If something massive moves quickly, then a wave can be set up and travel through space. Technically this happens whenever anything with mass moves, but space is stiff – it takes a good whack to get a detectable wave going, and so if we are to have

[1] Later designated a kilonova, but this is, from an observational point of view semantics. A kilanova is just a powerful supernova.

[2] Technical spacetime, but it makes no difference here if we just consider the three dimensions of space, and leave time out of it.

any hope of detecting gravitational waves, their sources are going to have to be some of the most extreme places in the Universe.

When Einstein presented general relativity in 1917, and for many years after, it was essentially considered a toy for mathematicians and the more theoretical kind of physicist, rather than anything which could be applied to astronomical observations. The crest of a wave produced by even such a violent event as two neutron stars colliding would cause a displacement of much less than the radius of an atomic nucleus, and for most of the twentieth century detecting such a small effect would have been considered a fool's errand. Einstein himself certainly never thought that the predicted gravitational waves would ever be detected.

This changed with the discovery in 1974 discovery by Russell Hulse and Joseph Taylor of a very special pulsar. Using the now sadly missed Arecibo radio telescope, they recorded and carefully timed the pulses coming from the system. Normally these would be regular – and to begin with they were, with a period of 59 milliseconds, but the pair of astronomers realised that the timing was off, with pulses arriving sometimes a little early, and sometimes a little late. This odd behaviour could be explained if the pulsar was in orbit around a massive object, most likely a neutron star, with a period of nearly eight hours.

The two behemoths are close together – at periastron, their closest, they are about a solar radii apart – and moving fast. As they whirl around, they stir up space, sending gravitational waves out into the cosmos, and losing energy as they do so. As a result, they must spiral together at a rate that we can precisely calculate – and which Hulse and Taylor detected as a change in period which has continued unabated over the last fifty years. For the first time, we had a system in which we could observe the effect of gravitational waves.

Meanwhile, back on Earth, a small band of experimental physicists were dreaming of more direct detections. Early attempts, involving monitoring large aluminium cylinders for ringing caused by the effects of passing waves – a sort of gravitationally powered xylophone - were quickly abandoned, and an approach involving the construction of giant interferometers was settled on.

In theory, these are simple experiments. A beam of light generated by a laser is split into two. The twin beams are sent off at right angles to each other, travelling two or three kilometres before hitting a mirror and returning to the start point. Assuming the two mirrors which reflect the beams back are at exactly the same distance from the start, the two beams will arrive back at the same time. If we get it wrong, and place one mirror a little further from the start than the other, then the two beams will arrive at different times, and will interfere with each other. If a gravitational wave passes through, though, the beam lines will be stretched or compressed, and we will see interference.

Simple enough, but the degree of accuracy required is astounding. Even when successful, LIGO and its sister experiments are looking for a change in length across its 4km arms[3] of about the same size as 1/10000$^{th}$ of a proton The rumbling of a distant truck, earthquakes small enough to let even the most sensitive sleeper lie, even the pecking of birds on the outside of the interferometer's structure[4], are all more significant that the signal that is being sought.

It was a long road to successful detection, with a gestation period nearly as long as that of the Hubble Space Telescope, which I discussed in the first lecture of this year's series. The first proposals for this sort of observatory were made in the 1960s, though nothing got further than the drawing board until the early 1980s. The small prototypes built in Germany, and then a little later at Caltech and MIT had arms that were only metres long, but they showed that the idea was sound, and did enough to unlock funding for the next generation of instruments, which might actually have a chance of success.

Physics on this scale often becomes a fight for funding, and the team led by Rainer Weiss (who had originally pitched the idea as a classwork problem for his students) and Kip Thorne, often had to justify their choices. They were adamant in particular that they needed two instruments, not just one – it cost much more, but that way they could be sure that if any signal was detected at both sites, it was real, and not the result of trucks or crows or anything else local. The sensitivity of the instrument depended on the size of the arms, too, and they ended up with a 3km range[5]. Critically, they also decided to get something running, even if the sensitivity was not high enough to make a detection likely, with a planned upgrade coming later on, once the team had gained experience with their detectors.

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[3] Long enough that the project's engineers need to account for the curvature of the Earth underneath their experiment.
[4] This is a real example; in the cold, dry conditions of the part of Washington that hosts LIGO, water freezing onto the chilled vacuum tube surrounding the beam is the best source of water for local crows.
[5] Though the light actually goes back and forth many hundreds of times, effectively increasing the size of the interferometer.

It was a long road. Initial approval to build the first version of the interferometers was granted in 1990, but the sensitivity that the physicists were aiming for was only reached in 2006. For four years, the LIGO team were able to sift through the data for evidence of gravitational waves, but nothing was found. The long-planned upgrade – with heavier test masses, better mirrors, and a more powerful isolating system – began in 2010 and took four years.

Equally important was the develop of new methods to predict, using supercomputers, what any signal LIGO found would look like. These predictions, requiring advances in the century old theory of general relativity, show what happens as two massive objects spiral together. As they do, the frequency of the gravitational waves increases, creating a 'chirp' – a rising tone that can be readily expressed in sound. If the two objects in question are black holes, their eventual coalescence into a single object produces a pattern rather like a bell, known as the ringdown, whose structure encodes much of the physics of these enigmatic objects.

It was therefore a triumph of both engineering and theoretical physics when, on September 14$^{th}$, 2015, while the team were still commissioning their newly upgraded instrument, LIGO detected a signal with the characteristic shape we'd expect from a collision of black holes. In the years since, through four long observing runs, LIGO, and its counterparts in Europe (VIRGO) and Japan (KAGRA) have made finding these exotic events almost routine. As a result, we now know more about these most enigmatic of objects than ever before.

The shape of the ringdown part of the gravitational wave tells us, for example, that the black holes are spinning; their motion drags space around with them, and we can see the effect. More importantly, we are beginning to build up a census of the masses of black holes involved in the collisions; the lightest seem to weigh in at about five solar masses, with the most massive detected being about ten times larger than that. This sort of demographic information is of great help for those trying to model the supernovae that form the black holes in the first place, and in understanding their effects on their surroundings.

Black holes are now core to the stories that we tell about the cosmos. The most convincing evidence for their existence comes from the centre of the Milky Way, were stars orbit an invisible massive object. The development of adaptive optics, which compensates for the movement of the Earth's atmosphere, has allowed astronomers to watch these stars move over the last few decades, producing evidence that there exists at our galaxy's centre an object of a few million solar masses crammed into a volume smaller than that occupied by our Solar System.

Long before this evidence could be obtained, black holes had captured the public imagination. There's something about the idea of an object which we cannot escape that captures the attention, but the fact that black holes are perhaps the best-known astronomical objects would have surprised the physicists who first noticed their presence, lurking in the equations of Einstein's general relativity. The idea of an object whose density is so large that it has a gravitational pull that nothing can escape goes back to the work of 18$^{th}$ century geologist John Michell[6], who wrote about 'dark stars'. It is relativity's notion that light travels at a fixed speed, and that the speed of light forms a cosmic speed limit that nothing can exceed that really shapes the idea of a black hole.

It was Karl Schwarzschild, freezing on the German army's Russian Front during the first world war, who in 1916 showed that Einstein's general relativistic equations have an exact solution, corresponding to a single, chargeless, static (non-rotating) body, but few expected such things to actually exist. The great Rutherford (self-styled as the only man other than Einstein, Schwarzschild having perished from a disease contracted at the front, to understand general relativity) insisted, in dispute with Chandrasekar that 'there should be a law of nature to prevent a star from behaving in this absurd way.' Even as physicists such as John Wheeler worked in the mid-twentieth century to rehabilitate the study of GR as a core part of physics, there was little expectation that the objects their equations describe would be real. (Wheeler seems to have been the popular source of the name 'black hole', which he claimed he'd introduced because a lecture audience got fed up of him saying 'compact gravitational source').

And yet the Universe has an almost boundless capacity to surprise us. When the first instruments capable of detecting x-rays from space flew in the 1960s, initially on sounding rockets and then on spacecraft, they found a strange new class of sources. The brightest, known as Cygnus X-1 was intensively studied by an orbiting observatory called Uhuru in 1970. It seemed to be flickering, changing on timescales that were

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[6] Described as 'so far ahead of his scientific contemporaries that his ideas languished in obscurity, until they were re-invented more than a century later', Michell's other claims to fame include being the first person to think about seismic waves. His ideas seem to have been forgotten for a century while everyone else caught up.

much shorter than a second – an indication that whatever the source was, it must be small. (Modern measurement show that Cygnus X-1 varies on timescales of a millisecond, which means the region the x-rays are coming from must be no more than a few hundred kilometres across) Follow up observations from the ground spotted a star in orbit around the mysterious x-ray source, which allowed its mass to be measured: 15 solar masses.

Compact massive objects were known – the discovery of pulsars, rapidly spinning neutron stars, was fresh in astronomers' mind – but there is a physical limit to how massive such objects can be. Around 3 solar masses seems to be the limit[7], and fifteen is right out. The only objects on the theoretical shelf that fitted the bill were black holes, components of this new class of x-ray binary star. This might seem confusing. We defined a black hole as a body that was so massive that even light cannot escape, and yet here I'm claiming that seeing x-rays – which are, after all, light – proves that black holes exist. Black holes are, as it turns out, incredibly efficient at producing light, and in the right circumstances, they do so with an efficiency that dwarfs that of normal stars like the Sun.

The key to this seeming paradox is to get away from the view of black holes as some sort of gravitational monsters, rampaging through the galaxy and acting like a cosmic vacuum cleaner. From a suitable distance, they are just a source of gravitational potential – you can, if you want, orbit a black hole perfectly safely, without any risk of falling in. It is only within the event horizon, a region whose size depends only on the mass of the black hole, that escape is impossible. (A little way further out, three times further if the black hole is not rotating, is the innermost stable orbit. Anything without engines within this radius is doomed to cross the event horizon eventually). As material falls towards the black hole, for example if it is ripped from a companion star in a binary system, it will take up orbits in the black hole's gravitational potential. In the resulting accretion disk, collisions between particles heat the material up, reaching temperatures of thousands of degrees and radiating energy away in the form of x-rays.

Of course, once material gets too close, it falls inevitably into the black hole itself. The crossing of the event horizon is likely uneventful; light, after all, can fall into the black hole even if it can't escape, and so a traveller crossing this cosmic Rubicon will still be able to see the surrounding Universe. However, the distorting effect of gravity on time mean that from an outside observer's perspective, the infalling object (or astronaut) will seem to take an infinite amount of time to reach the horizon[8]. If, that is, they resist the wonderfully named spaghettification caused by differential forces along the steep gravitational gradient near to the black hole itself.

While x-ray astronomers were getting to grips with the highly energetic sources that their telescopes revealed, those working with radio telescopes had a similar puzzle on their hands. Apparently distant sources covered the radio sky, with no apparent structure to distinguish them. These 'quasi-stellar', or starlike, were soon spotted using optical telescopes too, and their spectra revealed that they were distant, and hence extremely powerful. Maarten Schmidt, a Dutch astronomer working in the US, correctly identified them as distant active galactic nuclei, their light coming from accretion disks around supermassive black holes at the centre of distant galaxies, but the idea seemed outlandish at the time. Only in the late 1970s, when photographic and telescopic techniques had advanced to reveal the galaxies which hosted the quasars, was the idea finally accepted.

We now believe that every galaxy has a large black hole at its centre. Recent results from JWST have shown that such objects are firmly in place even in the first billion years of the Universe's history. This causes trouble for theorists trying to explain how they can possibly have grown so fast (exotic models, which do things like introduce dark matter cores in the centre of the first stars, in an effort to prolong their life and allow them to grow larger, producing larger black holes when they do, in fact, die), and it may be the case that black holes form first via some as yet dimly understood process, before the rest of a galaxy assembles around each of them. Tests of these ideas will become possible sometime in the next decade with the launch of the European Space Agency's LISA mission – a giant space-borne interferometer with light bouncing between three free-floating spacecraft millions of kilometres apart, it will be sensitive to the lower frequency gravitational waves emitted by the merging of supermassive black holes.

I have tried in this lecture to stick to what we know about black holes from observations, without getting lost in the theory. There is a rich set of theoretical games involving understanding the properties of a black hole

[7] This is often given as 2.25 solar masses, but rotation complicates things.

[8] If you are troubled by the apparent inconsistency of this statement with the fact that black holes do grow as material falls into them, then the key is to realise that the event horizon itself will shift outwards as more matter falls towards the central black hole.

itself, particularly in the thermodynamical treatment developed first by Roger Penrose and then by Stephen Hawking; the latter's most lasting contribution to physics is likely to be the as yet untested proposition that black holes do slowly evaporate via a process, we call Hawking radiation. What happens at the centre of the black hole, a place where our equations naively indicate the presence of a singularity, a point of infinite density, is equally obscure.

From the outside, we are limited by what is – ridiculously – called the 'No hair theorem'. It states that the only properties of a black hole that we can measure from outside the event horizon are its mass, angular momentum and charge. Yet black holes can surprise us, and their mysteries still inspire enormous efforts from physicists. The indefatigable Event Horizon Telescope team flew equipment to the South Pole as part of an effort to use telescopes scattered across the globe to get their famous image of the disk that surrounds the Milky Way's black hole and are still watching in the hope of watching it flicker and change as material falls towards its doom. More than a century after Schwarzschild wrangled the equations that describe them, black holes continue to fascinate us.

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## Reading List

- Pedro Ferreira's 'The Perfect Theory: Acentury of geniuses and the battle over General Relativity' (Abacus, 2015) is an excellent introduction to the field.
- 'A Crack in Everything: How Black Holes Came in from the Cold and Took Cosmic Centre Stage' (Apollo, 2024) by Marcus Chown concentrates on the enigmatic objects themselves.

The best books on LIGO are:

- 'Ripples on a cosmic sea' (Perseus, 1997) for the early history
- 'Gravity's Kiss' by Harry Collins (University of Chicago Press, 2018)

There is a curated library of papers produced by the LIGO collaboration here:
https://www.ligo.caltech.edu/page/ligo-publications

For GW170817, I especially enjoy the paper which describes the follow-up with the world's telescopes:
https://arxiv.org/abs/1710.05833

There is a nice summary of the Hulse-Taylor pulsar here:
https://astrobites.org/2018/02/02/looking-back-at-the-hulse-taylor-binary-pulsar/

A good popular article of the early Weber attempts to find gravitational waves is here:
https://www.forbes.com/sites/briankoberlein/2015/10/12/joseph-weber-and-the-failed-search-for-gravitational-waves/