

Transcript of Stephen Hawking's first Reith lecture

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With annotations by BBC Science Editor David Shukman

With appearances on comedy shows, books in the best-seller lists and the unforgettable image of a brilliant mind in an ailing body, Stephen Hawking has earned the title of the world's most famous scientist. His field has never been easy for a wider public to grasp: everything from the formation of the universe to those strange but dangerous features known as black holes. But his energy and humour, and his determination to reach a wider audience, have always produced an enthusiastic response. And that inevitably brings a lot more questions of the kind that people might find embarrassing to ask in public. So, as a guide for the interested but perplexed, I have added a few notes to the first of Stephen Hawking's BBC Reith Lectures.

My talk is on black holes. It is said that fact is sometimes stranger than fiction, and nowhere is that more true than in the case of black holes. Black holes are stranger than anything dreamed up by science fiction writers, but they are firmly matters of science fact. The scientific community was slow to realize that massive stars could collapse in on themselves, under their own gravity, and how the object left behind would behave. Albert Einstein even wrote a paper in 1939, claiming stars could not collapse under gravity, because matter could not be compressed beyond a certain point. Many scientists shared Einstein's gut feeling. The principal exception was the American scientist John Wheeler, who in many ways is the hero of the black hole story. In his work in the 1950s and '60s, he emphasized that many stars would eventually collapse, and the problems that posed for theoretical physics. He also foresaw many of the properties of the objects which collapsed stars become, that is, black holes.

DS: The phrase 'black hole' is simple enough but it's hard to imagine one out there in space. Think of a giant drain with water spiralling down into it. Once anything slips over the edge or 'event horizon', there is no return. Because black holes are so powerful, even light gets sucked in so we can't actually see them. But scientists know they exist because they rip apart stars and gas clouds that get too close to them.

During most of the life of a normal star, over many billions of years, it will support itself against its own gravity, by thermal pressure, caused by nuclear processes, which convert hydrogen into helium.

DS: NASA describes stars as rather like pressure-cookers. The explosive force of nuclear fusion inside them creates outward pressure which is constrained by gravity pulling everything inwards.

Eventually, however, the star will exhaust its nuclear fuel. The star will contract. In some cases, it may be able to support itself as a white dwarf star. However Subrahmanyan Chandrasekhar showed in 1930, that the maximum mass of a white dwarf star is about 1.4 times that of the Sun. A similar maximum mass was calculated by Soviet physicist, Lev Landau, for a star made entirely of neutrons.

DS: White dwarfs and neutron stars have exhausted their fuel so they have shrunk to become some of the densest objects in the universe. Most interesting to Stephen Hawking is what happens when the very biggest stars collapse in on themselves.

What would be the fate of those countless stars, with greater mass than a white dwarf or neutron star, when they had exhausted nuclear fuel? The problem was investigated by Robert Oppenheimer, of later atom bomb fame. In a couple of papers in 1939, with George Volkoff and Hartland Snyder, he showed that such a star could not be supported by pressure. And that if one neglected pressure, a uniform spherically symmetric star would contract to a single point of infinite density. Such a point is called a singularity.

DS: A singularity is what you end up with when a giant star is compressed to an unimaginably small point. This concept has been a defining theme in Stephen Hawking's career. It refers to the end of a star but also something more fundamental: that a singularity was the starting-point for the formation of the entire universe. It was Hawking's mathematical work on this that earned him global recognition.

All our theories of space are formulated on the assumption that spacetime is smooth and nearly flat, so they break down at the singularity, where the curvature of space-time is infinite. In fact, it marks the end of time itself. That is what Einstein found so objectionable.

DS: Einstein's Theory of General Relativity says that objects distort the spacetime around them. Picture a bowling-ball lying on a trampoline, changing the shape of the material and causing smaller objects to slide towards it. This is how the effect of gravity is explained. But if the curves in spacetime become deeper and deeper, and eventually infinite, the usual rules of space and time no longer apply.

Then the war intervened. Most scientists, including Robert Oppenheimer, switched their attention to nuclear physics, and the issue of gravitational collapse was largely forgotten. Interest in the subject revived with the discovery of distant objects, called quasars.

DS: Quasars are the brightest objects in the universe, and possibly the most distant detected so far. The name is short for 'quasi-stellar radio sources' and they are believed to be discs of matter swirling around black holes.

The first quasar, 3C273, was discovered in 1963. Many other quasars were soon discovered. They were bright, despite being at great distances. Nuclear processes could not account for their energy output, because they release only a percent fraction of their rest mass as pure energy. The only alternative was gravitational energy, released by gravitational collapse.

Gravitational collapses of stars were re-discovered. It was clear that a uniform spherical star would contract to a point of infinite density, a singularity.

The Einstein equations can't be defined at a singularity. This means at this point of infinite density, one can't predict the future. This implies something strange could happen whenever a star collapsed. We wouldn't be affected by the breakdown of prediction, if the singularities are not naked, that is, they are not shielded from the outside.

DS: A 'naked' singularity is a theoretical scenario in which a star collapses but an event horizon does not form around it – so the singularity would be visible.

When John Wheeler introduced the term black hole in 1967, it replaced the earlier name, frozen star. Wheeler's coinage emphasized that the remnants of collapsed stars are of interest in their own right, independently of how they were formed. The new name caught on quickly. It suggested something dark and mysterious, But the French, being French, saw a more risqué meaning. For years, they resisted the name *trou noir*, claiming it was obscene. But that was a bit like trying to stand against *Le Week-end*, and other *Franglais*. In the end, they had to give in. Who can resist a name that is such a winner?

From the outside, you can't tell what is inside a black hole. You can throw television sets, diamond rings, or even your worst enemies into a black hole, and all the black hole will remember is the total mass, and the state of rotation. John Wheeler is known for expressing this principle as “a black hole has no hair”. To the French, this just confirmed their suspicions.

A black hole has a boundary, called the event horizon. It is where gravity is just strong enough to drag light back, and prevent it escaping. Because nothing can travel faster than light, everything else will get dragged back also. Falling through the event horizon is a bit like going over Niagara Falls in a canoe. If you are above the falls, you can get away if you paddle fast enough, but once you are over the edge, you are lost. There's no way back. As you get nearer the falls, the current gets faster. This means it pulls harder on the front of the canoe than the back. There's a danger that the canoe will be pulled apart. It is the same with black holes. If you fall towards a black hole feet first, gravity will pull harder on your feet than your head, because they are nearer the black hole.

The result is you will be stretched out longwise, and squashed in sideways. If the black hole has a mass of a few times our sun you would be torn apart, and made into spaghetti before you reached the horizon. However, if you fell into a much larger black hole, with a mass of a million times the sun, you would reach the horizon without difficulty. So, if you want to explore the inside of a black hole, make sure you choose a big one. There is a black hole with a mass of about four million times that of the sun, at the centre of our Milky Way galaxy.

DS: Scientists believe that there are huge black holes at the centre of virtually all galaxies – a remarkable thought, given how recently these features were confirmed in the first place.

Although you wouldn't notice anything particular as you fell into a black hole, someone watching you from a distance would never see you cross the event horizon. Instead, you would appear to slow down, and hover just outside. Your image would get dimmer and dimmer, and redder and redder, until you were effectively lost from sight. As far as the outside world is concerned, you would be lost for ever.

There was a dramatic advance in our understanding of these mysterious phenomena with a mathematical discovery in 1970. This was that the surface area of the event horizon, the boundary of a black hole, has the property that it always increases when additional matter or radiation falls into the black hole. These properties suggest that there is a resemblance

between the area of the event horizon of a black hole, and conventional Newtonian physics, specifically the concept of entropy in thermodynamics. Entropy can be regarded as a measure of the disorder of a system, or equivalently, as a lack of knowledge of its precise state. The famous second law of thermodynamics says that entropy always increases with time. This discovery was the first hint of this crucial connection.

DS: Entropy means the tendency for anything that has order to become more disordered as time passes – so, for example, bricks neatly stacked to form a wall (low entropy) will eventually end up in an untidy heap of dust (high entropy). And this process is described by the second law of thermodynamics.

Although there is clearly a similarity between entropy and the area of the event horizon, it was not obvious to us how the area could be identified as the entropy of a black hole itself. What would be meant by the entropy of a black hole? The crucial suggestion was made in 1972 by Jacob Bekenstein, who was a graduate student at Princeton University, and then at the Hebrew University of Jerusalem. It goes like this. When a black hole is created by gravitational collapse, it rapidly settles down to a stationary state, which is characterized by only three parameters: the mass, the angular momentum, and the electric charge. Apart from these three properties, the black hole preserves no other details of the object that collapsed.

His theorem has implications for information, in the cosmologist's sense of information: the idea that every particle and every force in the universe has an implicit answer to a yes-no question.

DS: Information, in this context, means all the details of every particle and force associated with an object. And the more disordered something is – the higher its entropy - the more information is needed to describe it. As the physicist and broadcaster Jim Al-Khalili puts it, a well-shuffled pack of cards has higher entropy and therefore needs far more explanation, or information, than an unshuffled one.

The theorem implies that a large amount of information is lost in a gravitational collapse. For example, the final black-hole state is independent of whether the body that collapsed was composed of matter or antimatter, or whether it was spherical or highly irregular in shape. In other words, a black hole of a given mass, angular momentum and electric charge, could have been formed by the collapse of any one of a large number of different configurations of matter. So what appears to be the same black hole could be formed by the collapse of a large number of different types of star. Indeed, if quantum effects are neglected, the number of configurations would be infinite, since the black hole could have been formed by the collapse of a cloud of an indefinitely large number of particles, of indefinitely low mass. But could the number of configurations really be infinite?

The uncertainty principle of quantum mechanics implies that only particles with a wavelength smaller than that of the black hole itself could form a black hole. That means the wavelength would be limited: it could not be infinite.

DS: The uncertainty principle, conceived by the famous German physicist Werner Heisenberg, describes how we can never locate or predict the precise position of the smallest particles. So, at

what is called the quantum scale, there is a fuzziness in nature, very unlike the more ordered universe described by Isaac Newton.

It therefore appears that the number of configurations that could form a black hole of a given mass, angular momentum and electric charge, although very large, may also be finite. Jacob Bekenstein suggested that from this finite number, one could interpret the entropy of a black hole. This would be a measure of the amount of information that was irretrievably lost during the collapse when a black hole was created.

The apparently fatal flaw in Bekenstein's suggestion was that if a black hole has a finite entropy that is proportional to the area of its event horizon, it also ought to have a finite temperature, which would be proportional to its surface gravity. This would imply that a black hole could be in equilibrium with thermal radiation, at some temperature other than zero. Yet according to classical concepts, no such equilibrium is possible, since the black hole would absorb any thermal radiation that fell on it, but by definition would not be able to emit anything in return. It cannot emit anything. It cannot emit heat.

DS: If information is lost, which is apparently what is happening in a black hole, there should be some release of energy - but that flies in the face of the theory that nothing comes out of black holes.

This is a paradox. And it's one which I am going to return to in my next lecture, when I'll be exploring how black holes challenge the most basic principle about the predictability of the universe, and the certainty of history, and asking what would happen if you ever got sucked into one. Thank you.

DS: So Stephen Hawking has taken us on a scientific journey from Einstein's claim that stars could not collapse to the acceptance of the reality of black holes to a collision of theories over how these weird features exist and function.

The second lecture will bring us up to date with the latest thinking on black holes, and will ask us to change the way we think of them.

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Transcript of audience Q and A after the first lecture

SUE LAWLEY: Thank you. Thank you very much indeed, Stephen. Well now we asked listeners what they'd like to ask you and their questions came flooding in, hundreds of them. We've chosen a representative selection of topics and invited some of those listeners to

come and put their questions in person. You'll appreciate, audience, that we had to give Stephen the questions beforehand, so that he could programme his answers into his computer. This is done letter by letter through the movement of his facial muscles and you'll hear little tiny bleeps as the infrared detector picks up those movements. It's not a speedy process, round about a word a minute, but the answers are all in there now. So if you're ready, Professor, let me begin by asking Andy Fabian, who's an astronomer and astrophysicist – he's the Director of the Institute of Astronomy at Cambridge and therefore a colleague of Stephen's – Andy, your question please?

ANDY FABIAN: Stephen, much of the work by yourself and others on issues such as the potential loss of information in black holes and on radiation from black holes is theoretical and lacks observational support so far. Do you see ways to change that situation using the many and varied observations now routinely being made of accreting black holes throughout the cosmos?

SUE LAWLEY: Stephen?

STEPHEN HAWKING: I assume you are referring to the area increase law for black hole horizons. The best way of testing this is black hole collisions rather than accretion.

SUE LAWLEY: Well you got pretty short shrift there, I have to say. *(laughter)* Perhaps you should tell us what the difference is between accreting black holes and black hole collisions?

ANDY FABIAN: Well black hole collisions are when you have two black holes colliding with each other and merging together. Accretion is just matter dribbling into the black hole steadily and it produces enormous amounts of energy release, very luminous things in the universe.

SUE LAWLEY: Do you foresee that there will be evidential proof of what Stephen is talking about? As you say, it's all theoretical at the moment.

ANDY FABIAN: It would be fantastic to find observational proof of it, but I myself don't see how to do it.

SUE LAWLEY: Okay well let's pursue this theme of what black holes get up to when we're looking at them, and indeed when we're not, and turn to a group of young enthusiasts here from the West Midlands. They're pupils from Barr Beacon Secondary School in Walsall and they're aged around 12 or 13. Kate Harris, you're their teacher. How have you got them interested in cosmology and everything else?

KATE HARRIS: Well I'm their form tutor, so I look after them every morning. I received an email from one of the science teachers who's with us, Dr Butterworth, about Stephen's lecture and told them about it. And they were so keen to know more because firstly they've seen him in 'The Big Bang Theory'... *(laughter)*

SUE LAWLEY: This is the television ... the American sitcom?

KATE HARRIS: Yes. And also they are keen science enthusiasts. They just wanted to know more.

SUE LAWLEY: Yeah, so endlessly interested. Well let's have a question from one of them. Aruniya Muraleedaran, you're aged 12. What's your question?

ARUNYA MURALEEDARAN: What kind of things would happen if one black hole collided with another one?

STEPHEN HAWKING: If two black holes collide and merge to form a single black hole, the area of the event horizon around the resulting black hole is greater than the sum of the areas of the event horizons around the original black holes.

SUE LAWLEY: Did you understand that, Aruniya? Did you get your head round it? *(laughter)* Well, as I understand it, it's when two black holes collide, the total circumference is greater than the sum of the two parts. The whole area increases. Got it?

ARUNYA MURALEEDARAN: I've got it now. *(laughter)* What about you? Did you ... Do you want to say something?

STUDENT: Yeah, I did understand it.

SUE LAWLEY: You did?

STUDENT: A bit, a bit. *(laughter)*

APPLAUSE

SUE LAWLEY: Well maybe it was because I explained it to you. *(laughter)* Now to a rather more personal question – and we received many of them actually. This is from a 17 year old Radio 4 listener. His name is Duncan McKinnon. You told us, Duncan, that Stephen had been an inspiration to you. In what way?

DUNCAN McKINNON: Well watching the film with him, it was really inspirational how he managed to carry on with his dreams and goals.

SUE LAWLEY: You mean the film 'The Theory of Everything' ...

DUNCAN McKINNON: Yeah, yeah.

SUE LAWLEY: ... which starred Eddie Redmayne ...

DUNCAN McKINNON: Yeah.

SUE LAWLEY: ... for which he won an Oscar of course. Great film, wasn't it? Okay, like to put your question?

DUNCAN McKINNON: I would like to ask you what inspired you to keep on going despite all the rough times in your life?

SUE LAWLEY: Stephen?

STEPHEN HAWKING: I think my work and a sense of humour have kept me going. When I turned 21 my expectations were reduced to zero. You probably know this already because there's been a movie about it. In this situation, it was important that I came to appreciate what I did have. Although I was unfortunate to get motor neurone disease, I have been very fortunate in almost everything else. I have been lucky to work in theoretical physics at a fascinating time, and it's one of the few areas in which my disability was not a serious handicap. It's also important not to become angry, no matter how difficult life may seem, because you can lose all hope if you can't laugh at yourself and life in general.

SUE LAWLEY: We have here Lucy Hawking, Stephen's daughter, just towards the front there. Lucy, you have seen Stephen over the past four decades if you don't mind my saying that. *(laughter)*

LUCY HAWKING: That's a little personal, Sue. *(laughter)*

SUE LAWLEY: I apologise, Lucy.

LUCY HAWKING: That's okay. It's radio, Sue.

STEPHEN HAWKING: *(interjecting)* I would bring back Einstein. *(laughter)*

SUE LAWLEY: Interjection from my right. You've seen him, Lucy, weather some pretty rough times. What do you put his resilience and this determination down to?

LUCY HAWKING: I think he's enormously stubborn *(laughter)* and has a very enviable wish to keep going and the ability to summon all his reserves, all his energy, all his mental focus and press them all into that goal of keeping going. But not just to keep going for the purposes of survival, but to transcend this by producing extraordinary work, writing books, giving lectures, inspiring other people with neurodegenerative and other disabilities, and being a family man, a friend and a colleague to so many ... so many people and keeping up with friends across the world. So I think there ... there are lots and lots of elements there, but I do think the stubbornness, the will to live and – like he says himself – the sense of humour to laugh at it, at the end of the day is what has ...

STEPHEN HAWKING: *(interjecting)* I would bring back Einstein. *(laughter/applause)* He would be amazed at how much general relativity has advanced our understanding of the world.

LUCY HAWKING: I think that was his way of asking me to stop talking. *(laughter)*

SUE LAWLEY: And there we must end. Thank you for making this a memorable event. There's a mass of science on the BBC Reith website, including Robert Oppenheimer, whom Stephen mentioned – one of the fathers of the atom bomb; the astrophysicist Martin Rees; the radio astronomer Bernard Lovell and many more. There's an archive of recordings and transcripts going back to 1948, so do have a look.

For now our thanks to our hosts here at the Royal Institution in London and of course huge thanks to our Reith Lecturer, Professor Stephen Hawking.

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