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THE REITH LECTURES 2015

Reith Lecturer: Professor STEPHEN HAWKING

Lecture 2: Black holes ain't as black as they are painted

SUE LAWLEY: Hello and welcome to the second in this series of BBC Reith Lectures. We're at the Royal Institution in London. Last week our lecturer described the history of scientific thinking about black holes, and how they've posed difficult questions for the conventional understanding of the laws which govern our universe. He told us that these collapsed stars challenge the very nature of space and time, as they become a singularity - a point of infinite density at which the normal rules of physics break down. In this second lecture, he'll address the idea that nothing can ever emerge from a black hole, that they destroy any information they suck in. Or do they? The title of this lecture is 'Black holes ain't as black as they are painted.' Ladies & Gentlemen, please welcome the BBC's Reith Lecturer, Professor Stephen Hawking.

APPLAUSE

STEPHEN HAWKING: Can you hear me? In my previous lecture I left you on a cliffhanger: a paradox about the nature of black holes, the incredibly dense objects created by the collapse of stars. One theory suggested that black holes with identical qualities could be formed from an infinite number of different types of stars. Another suggested that the number could be finite. This is a problem of information, that is the idea that every particle and every force in the universe contains information, an implicit answer to a yes-no question.

Because black holes have no hair, as the scientist John Wheeler put it, one can't tell from the outside what is inside a black hole, apart from its mass, electric charge, and rotation. This means that a black hole contains a lot of information that is hidden from the outside world. If the amount of hidden information inside a black hole depends on the size of the hole, one would expect from general principles that the black hole would have a temperature, and would glow like a piece of hot metal. But that was impossible, because as everyone knew, nothing could get out of a black hole. Or so it was thought.

This problem remained until early in 1974, when I was investigating what the behaviour of matter in the vicinity of a black hole would be, according to quantum mechanics. To my great surprise I found that the black hole seemed to emit particles at a steady rate. Like everyone else at that time, I accepted the dictum that a black hole could not emit anything. I therefore put quite a lot of effort into trying to get rid of this embarrassing effect. But the more I thought about it, the more it refused to go away, so that in the end I had to accept it. What finally convinced me it was a real physical process was that the outgoing particles have a spectrum that is precisely thermal. My calculations predicted that a black hole creates and emits particles and radiation, just as if it were an ordinary hot body, with a temperature that is proportional to the surface gravity, and inversely proportional to the mass.

Since that time, the mathematical evidence that black holes emit thermal radiation has been confirmed by a number of other people with various different approaches. One way to understand the emission is as follows. Quantum mechanics implies that the whole of space is filled with pairs of virtual particles and antiparticles that are constantly materializing in pairs, separating, and then coming together again, and annihilating each other. These particles are called virtual because unlike real particles they cannot be observed directly with a particle detector. Their indirect effects can nonetheless be measured, and their existence has been confirmed by a small shift, called the Lamb shift, which they produce in the spectrum energy of light from excited hydrogen atoms. Now in the presence of a black hole, one member of a pair of virtual particles may fall into the hole, leaving the other member without a partner with which to annihilate. The forsaken particle or antiparticle may fall into the black hole after its partner, but it may also escape to infinity, where it appears to be radiation emitted by the black hole.

A black hole of the mass of the sun, would leak particles at such a slow rate, it would be impossible to detect. However, there could be much smaller mini black holes with the mass of say, a mountain. A mountain-sized black hole would give off x-rays and gamma rays, at a rate of about ten million megawatts, enough to power the world's electricity supply. It wouldn't be easy however, to harness a mini black hole. You couldn't keep it in a power station, because it would drop through the floor and end up at the centre of the Earth. If we had such a black hole, about the only way to keep hold of it would be to have it in orbit around the Earth.

People have searched for mini black holes of this mass, but have so far not found any. This is a pity, because if they had I would have got a Nobel Prize. *(laughter)* Another possibility, however, is that we might be able to create micro black holes in the extra dimensions of space time. According to some theories, the universe we experience is just a four dimensional surface in a ten or eleven dimensional space. The movie Interstellar gives some idea of what this is like. We wouldn't see these extra dimensions because light wouldn't propagate through them but only through the four dimensions of our universe. Gravity, however, would affect the extra dimensions and would be much stronger than in our universe. This would make it much easier to form a little black hole in the extra dimensions. It might be possible to observe this at the LHC, the Large Hadron Collider, at CERN in Switzerland. This consists of a circular tunnel, 27 kilometres long. Two beams of particles travel round this tunnel in opposite directions, and are made to collide. Some of the collisions might create micro black holes. These would radiate particles in a pattern that would be easy to recognize. So I might get a Nobel Prize after all. *(laughter)*

As particles escape from a black hole, the hole will lose mass, and shrink. This will increase the rate of emission of particles. Eventually, the black hole will lose all its mass, and disappear. What then happens to all the particles and unlucky astronauts that fell into the black hole? They can't just re-emerge when the black hole disappears. It appears that the information about what fell in is lost, apart from the total amount of mass, and the amount of rotation. But if information is lost, this raises a serious problem that strikes at the heart of our understanding of science. For more than 200 years, we have believed in scientific determinism, that is, that the laws of science determine the evolution of the universe. This was formulated by Pierre-Simon Laplace, who said that if we know the state of the universe at one time, the laws of science will determine it at all future and past times. Napoleon is said to have asked Laplace how God fitted into this picture. Laplace replied, “Sire, I have not needed that hypothesis.” I don't think that Laplace was claiming that God didn't exist. It is just that he doesn't intervene to break the laws of science. That must be the position of every scientist. A scientific law is not a scientific law if it only holds when some supernatural being decides to let things run and not intervene.

In Laplace's determinism, one needed to know the positions and speeds of all particles at one time, in order to predict the future. But there's the uncertainty relationship, discovered by Walter Heisenberg in 1923, which lies at the heart of quantum mechanics. This holds that the more accurately you know the positions of particles, the less accurately you can know their speeds, and vice versa. In other words, you can't know both the positions and the speeds accurately. How then can you predict the future accurately? The answer is that although one can't predict the positions and speeds separately, one can predict what is called the quantum state. This is something from which both positions and speeds can be calculated to a certain degree of accuracy. We would still expect the universe to be deterministic, in the sense that if we knew the quantum state of the universe at one time, the laws of science should enable us to predict it at any other time.

If information were lost in black holes, we wouldn't be able to predict the future, because a black hole could emit any collection of particles. It could emit a working television set, or a leather-bound volume of the complete works of Shakespeare, though the chance of such exotic emissions is very low. It might seem that it wouldn't matter very much if we couldn't predict what comes out of black holes. There aren't any black holes near us. But it is a matter of principle. If determinism, the predictability of the universe, breaks down with black holes, it could break down in other situations. Even worse, if determinism breaks down, we can't be sure of our past history either. The history books and our memories could just be illusions. It is the past that tells us who we are. Without it, we lose our identity.

It was therefore very important to determine whether information really was lost in black holes, or whether in principle, it could be recovered. Many scientists felt that information should not be lost, but no one could suggest a mechanism by which it could be preserved. The arguments went on for years. Finally, I found what I think is the answer. It depends on the idea of Richard Feynman, that there isn't a single history, but many different possible histories, each with their own probability. In this case, there are two kinds of history. In one, there is a black hole, into which particles can fall, but in the other kind there is no black hole. The point is that from the outside, one can't be certain whether there is a black hole or not. So there is always a chance that there isn't a black hole. This possibility is enough to preserve the information, but the information is not returned in a very useful form. It is like burning an encyclopaedia. Information is not lost if you keep all the smoke and ashes, but it is difficult to read. The scientist Kip Thorne and I had a bet with another physicist, John Preskill, that information would be lost in black holes. When I discovered how information could be preserved, I conceded the bet. I gave John Preskill an encyclopaedia. Maybe I should have just given him the ashes. *(laughter)*

Currently I'm working with my Cambridge colleague Malcolm Perry and Andrew Strominger from Harvard on a new theory based on a mathematical idea called supertranslations to explain the mechanism by which information is returned out of the black hole. The information is encoded on the horizon of the black hole. Watch this space. *(laughter)*

What does this tell us about whether it is possible to fall in a black hole, and come out in another universe? The existence of alternative histories with black holes suggests this might be possible. The hole would need to be large, and if it was rotating, it might have a passage to another universe. But you couldn't come back to our universe. So although I'm keen on space flight, I'm not going to try that. *(laughter)*

The message of this lecture is that black holes ain't as black as they are painted. They are not the eternal prisons they were once thought. Things can get out of a black hole, both to the outside, and possibly to another universe. So if you feel you are in a black hole, don't give up. There's a way out. *(laughter)*

Thank you very much.

APPLAUSE

SUE LAWLEY: Professor Hawking, thank you very much indeed. So we've been taken on a trip to the outer regions of the universe, to the brink of human understanding and beyond. Listeners have sent in hundreds of questions for the professor and some of them are here with us now in the lecture theatre of the Royal Institution in London to put their questions in person. Can we have our first questioner, please? She's Marie Griffiths who comes from Godalming in Surrey, a civil servant at the Department for Education and has always been interested in physics. Your question, please, Marie?

MARIE GRIFFITHS: Did the Big Bang start just one universe or all the multiverses?

SUE LAWLEY: Stephen?

STEPHEN HAWKING: Some theories about the Big Bang allow for the creation of a very large and complex universe, maybe even many universes. However, even if there were other universes, we wouldn't know about them. Our connected component of space time is all we can know.

SUE LAWLEY: It's all we can know, Marie. And it's quite enough, by the sound of it. Let's have our next question – a question from John Brookmyre from Middlesbrough who describes himself as an ordinary working bloke and a lifelong learner. He couldn't unfortunately get here today, but let me put his question to you for him, Stephen. If you were a time lord, what moment in time would interest you and why?

STEPHEN HAWKING: I would like to meet Galileo. He was the first modern scientist, who realized the importance of observation. Galileo was the first person to challenge the received wisdom that the ancient Greeks, and Aristotle in particular, were the ultimate authority in science. Galileo pointed out that simple observations, like dropping weights from a height, show things do not work the way Aristotle said. This must have been seen by many people, but they had put it down to imperfect observations, or other reasons. But Galileo said the ancients were actually wrong and started to work out the correct laws from the observations. That makes him the father of modern science. He followed his nose, and was a bit of a rebel. *(laughter)*

SUE LAWLEY: A rebel who was forced to recant, of course. Right I'm going to come to Dara O'Briain over here on the right. Dara, the entertainer and science graduate. He studied pure mathematics and theoretical physics at University College Dublin in preparation for his career as a stand-up comic. *(laughter)* So you're an expert, are you Dara, on both physics and humour?

DARA O'BRIAIN: Yes, yeah, we overlap in some ways. Given that Stephen has appeared twice in The Simpsons, he has a more successful comedy career than I do. *(laughter)*

SUE LAWLEY: But he was your boyhood hero, wasn't he?

DARA O'BRIAIN: There was a huge … Yes I remember receiving a copy of A Brief History of Time for my Christmas when I was about 16. I had the pleasure this year of meeting him and having it autographed as it were and spending some time with Stephen this year. It was an honour.

SUE LAWLEY: Okay ask him another question.

DARA O'BRIAIN: Well actually given the chance, I turned the opportunity of this question over to some physicists I know – in particular Jim Al-Khalili. Professor Jim Al-Khalili wanted to ask a question from within the scientific community. As he said, most of the people in the physics community would indeed see the confirmation of Hawking radiation, which Professor Hawking invented in 1974, as being worthy of a Nobel Prize since it would have been the first theoretical prediction that required both quantum mechanics and relativity. Does Professor Hawking believe that Hawking radiation will be observed in his lifetime? And if it is observed, where does he think this experimental evidence will come from?

STEPHEN HAWKING: I am resigned to the fact that I won't see proof of Hawking radiation directly, though there are solid state analogues of black holes and cyclotron effects that the Nobel committee might accept as proof. *(laughter)* But there's another kind of Hawking radiation coming from the cosmological event horizon of the early inflationary universe. I'm now studying whether one might detect Hawking radiation in primordial gravitational waves. So I might get a Nobel Prize after all.

SUE LAWLEY: *(laughter)* A new kind of Hawking radiation then from light years earlier. Does that excite you Dara?

DARA O'BRIAIN: It does say one thing, however – that the work that Professor Hawking's been doing, theoretically and has been doing??, has skipped so far ahead of what we can do experimentally that there will be for a long time people racing to keep up with this work.

SUE LAWLEY: So I dare say you think that, whatever happens, he should get the Nobel Prize, huh?

DARA O'BRIAIN: If it was done by public acclaim, if it was a phone vote, *(laughter)* but the Swedes are notoriously sticky about that kind of stuff. So yeah, but I do believe - yes.

SUE LAWLEY: Okay. Chris Cooke, a 25 year old product designer from Crawley in Sussex. Chris studied mechanical engineering, so he's always been interested in physics. In his spare time, he does stand-up comedy, Dara, "despite my introverted … *(laughter)* despite my introverted personality traits", he says. Chris, your question?

CHRIS COOKE: Do you feel that using a speech device to communicate has changed your personality in any way? As an introvert, has it made you more extroverted?

SUE LAWLEY: Stephen?

STEPHEN HAWKING: Well I am not sure I have ever been called an introvert before. *(laughter)* Just because I spend a lot of time thinking doesn't mean I don't like parties and getting into trouble. *(laughter)* I enjoy communicating and I enjoy giving popular lectures about science. My speech synthesizer has been very important for this, even though I ended up with an American accent. *(laughter)* Before I lost my voice, my speech was slurred, so only those close to me could understand, but with the computer voice I found I could talk to everyone without help. So it has allowed me to express my personality rather than changing it.

SUE LAWLEY: Thank you very much for that question. Another questioner, Patrick Donaghue. He's a set designer who lives and works in London. Your question, Patrick?

PATRICK DONAGUE: Professor Hawking, do you think the world will end naturally or will man destroy it first?

SUE LAWLEY: Professor Hawking, just a small question. *(laughter)*

STEPHEN HAWKING: We face a number of threats to our survival from nuclear war, catastrophic global warming, and genetically engineered viruses. The number is likely to increase in the future, with the development of new technologies, and new ways things can go wrong. Although the chance of a disaster to planet Earth in a given year may be quite low, it adds up over time, and becomes a near certainty in the next thousand or ten thousand years. By that time we should have spread out into space, and to other stars, so a disaster on Earth would not mean the end of the human race. However, we will not establish self-sustaining colonies in space for at least the next hundred years, so we have to be very careful in this period. *(laughter)* Most of the threats we face come from the progress we have made in science and technology. We are not going to stop making progress, or reverse it, so we have to recognize the dangers and control them. I'm an optimist, and I believe we can.

SUE LAWLEY: Well I don't know about the world, but we're definitely running out of time. We've got one last question from Tara Struthers who's originally from the Orkneys, which may account for her lifelong interest in astronomy. These days she works for a film production company.

TARA STRUTHERS: If you had to offer one piece of advice for future generations of scientists, namely physicists and cosmologists, what would it be?

STEPHEN HAWKING: Science is a great enterprise and I want to share my excitement and enthusiasm about its success. From my own perspective, it has been a glorious time to be alive and doing research in theoretical physics. There is nothing like the Eureka moment of discovering something that no one knew before. So my advice to young scientists is to be curious, and try to make sense of what you see. We live in a universe governed by rational laws that we can discover and understand. Despite recent triumphs, there are many new and deep mysteries that remain for you to solve. And keep a sense of wonder about our vast and complex universe and what makes it exist. But you also must remember that science and technology are changing our world dramatically, so it's important to ensure that these changes are heading in the right directions. In a democratic society, this means that everyone needs to have a basic understanding of science to make informed decisions about the future. So communicate plainly what you are trying to do in science, and who knows, you might even end up understanding it yourself. *(laughter)*

SUE LAWLEY: And there we must end.

Newton was once asked how he'd managed to understand so much about the laws of the universe and he answered: "*by thinking of these things continually.*" Those of us who rely on others to do their thinking for them, are very glad that we have men like Stephen Hawking.

His lectures will be available on the BBC Reith website where you'll find recordings, transcripts and videos - an archive of all 67 series of Reith Lectures going back to 1948.

For now, from the Royal Institution in London, our thanks to the BBC Reith Lecturer Professor Stephen Hawking. And goodbye.

APPLAUSE