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Black Holes

Melvyn Bragg : Hello, black holes have been described as "the dead collapsed ghosts of massive stars". They have an irresistible gravitational pull, even light submits. Their dark swirling ever hungry mass has fascinated thinkers as diverse as Edgar Allen Poe, Stephen Hawking and countless science fiction writers. When their ominous existence was first predicted by the Rev John Mitchell in a paper to the Royal Society in 1783, nobody knew what to make of the idea, they couldn't be seen by any telescope. (indistinct) suggested by the 18th century Marquee de la Place, and their existence was proved on paper by the equations of Einstein's General Theory of Relativity, it was not until 1970 that Cygnus X-1 - the first black hole was put on the astral map.

What causes black holes? Do they play a role in the formation of galaxies? Will they eventually swallow everything up? And what have we learned of their nature since we found out where they are? With me on this voyage into the black hole is the Astronomer Royal Sir Martin Reece, author of many books including "Before the beginning : our universe and others", he's professor of physics and astronomy at Cambridge University.

Jocelyn Bell-Burnell, professor of physics at the Open University, and professor Martin Ward, director of the X-Ray astronomy group at the University of Leicester
Martin Reece you have described them to us as collapsed stars, these black holes , can you give a description of how a star collapses and how it becomes a black hole?

Martin Reece : A star is held together by gravity and the smaller a star gets or the heavier the star is the stronger gravity is. We know that in the case of the Earth, gravity is what holds us down, that's why Gagarin had to have a fast rocket to escape the escape from Earth's gravity, and to escape from the surface of a normal star, you would have to fire a rocket at about a thousand kilometres per second . But if you imagine something which is much smaller than a star, or much heavier a star, the speed you need to escape from it becomes much larger and eventually it may become so large that not even light can escape, and a black hole is an object where gravity has overwhelmed all other forces, and is contracted so much that not even light can escape from it. So a black hole is an object in space that exerts a gravitational imprint on its surroundings, but which puts out no light. Everything has collapsed, light can fall in, objects can fall in but nothing can get out because space is so warped as it were, that not even light can escape.

Melvyn Bragg : Right, now that's very clear, but there's a lot of ideas in side that, so I just want to go back over it quietly. This star collapses, gravity - that is the pull of the star towards the centre of itself -towards a singularity - becomes fiercer and fiercer and heavier and heavier, therefore to get away from it, it becomes harder, and even light travelling at 160, 000 miles per second, is not fast enough to get away from this. Now why does...what causes the collapse of the star in the first place and can you tell us, can you just explain a little about what you call escape velocity, about getting out - like Gagarin got out - like we fired a rocket - it's quite easy to get out of the Earth - it's harder to get out of the Sun as I understand it...

Martin Reece : Right.

Melvyn Bragg : It's impossible to get out of a black hole, now can you just go into that a little bit more?

Martin Reece : Yes well if the Sun was smaller it would be harder to escape, and indeed we do have objects which are not quite black holes, but their gravity's very strong. In fact these are objects called neutron stars, which Jocelyn Bell-Burnell here was co-discoverer of, a neutron star is an object which is as heavy as the sun, in other words a million times as heavy as the Earth, but is no bigger than the size of London, and on an object like that, gravity is clearly immensely strong, so strong that you have to fire your rocket at half the speed of light to escape. If you're on a neutron star, and you dropped your pen on the floor, it would not just make a noise, it would produce as much energy as a kilotonne of high explosive. So that's a measure of how strong gravity is when you have a very large mass in a small space. Now if you take a neutron star and imagine compressing it a factor of 3 smaller still, down to a size of say 3 miles across rather than 10, not even light could get out, and then it would be a completely dark object seen from outside, and it would become a black hole where something happens inside it that we can never understand, but to the outside world, it's just something which exerts a gravitational pull and nothing else.

Melvyn Bragg : I want to come back to you on one or two matters, but can you ...can you just...is it - I know these are enormous question, and it is just after 9 o'clock in the morning - but what is the main cause of a star collapsing?

Martin Reece : Well a star is held up by a very hot interior. Gravity pulls it in, but it's very hot inside, and a star is kept hot, in it's interior by nuclear fuel - the same kind of fusion processes that happens in an H-bomb, it happens in a controlled way inside stars, but when a star runs out of fuel, it will face a crisis, and for heavy stars, this crisis is solved by an implosion, which may lead to a neutron star and may lead to a black hole. So gravity always wins if fuel sources run out, and in a large star when gravity wins, it pulls all the material that was in the star together and much of it ends up in a black hole. So gravity always wins if there's no pressure or heat to oppose it.

Melvyn Bragg : Right, and Jocelyn Bell-Burnell, when the Rev John Mitchell announced in 19...sorry in 1783 a definition of a black hole, which is a brilliant three line definition, it reads very clearly now, as clearly as you could...of course nobody could as it were pick it up at all, and so on. What interests me though - because he was ahead of his time - but what interests me is how he got there without Einstein, without telescopes, without technology, can you tell me how he arrived at that conclusion, which is only over the last 30 or 40 years has been explored in any sort of certainty by people like yourselves?

Jocelyn Bell-Burnell : He was working with a picture of light that was invented by Sir Isaac Newton, it's called the corpuscular theory of light , which is still a picture that we use in many, many ways in contemporary science, and what Newton envisaged, was that light was a stream of little bullet-like things, little particles, and that each of these corpuscles actually had weight, and gravity would pull on that weight, just like if you try and lift a bottle of water, light would have a weight like the bottle of water and gravity would be pulling it back, and what Mitchell was doing was saying "How much gravity does there have to be, to pull the light back and stop it escaping?" and that at heart is what he was doing, and Lapasse I think a few years later was doing the same kind of thing.

Melvyn Bragg : So it was a thought experiment, as simple as that?

Jocelyn Bell-Burnell : Yes, yes, and I guess....

Melvyn Bragg : I'm still intrigued that working from Newton he got as it were beyond Einstein?

Jocelyn Bell-Burnell : It's an alternative way of looking at things. You quite often find in science that there are parallel ways of looking at things, parallel pictures, parallel movies is perhaps the best way to describe them, and as scientists we often use a lot of different pictures to help us understand. All the time you've got to remember that it is a picture, it may not be the actual thing, and that there are times when these pictures or analogies will let you down. So he was using a picture that one *could* still use today, but we don't happen to use very often.

Melvyn Bragg : Was that ever taken up? Do we know of the existence of his theory now because of what we know now, rather than people taking it up and saying "Ah Mitchell said that in 1783, I can build on that and develop from there"?

Jocelyn Bell-Burnell : I think...my guess is that we know of it because of hindsight, I think at the time it probably didn't make a great impact. People would have said "Oh that's an interesting calculation, pity it ain't relevant to the real world" and passed on, and it was only much, much later that the topic was revisited and I guess that Mitchell's quote in the past, this quote was subsequently dug out again and people said "Oh look, they thought of this way back in 1784" or whatever.

Melvyn Bragg : Martin Ward, is it unusual in science that something is discovered theoretically first and then found much later as it seems to be the case with the black holes?

Martin Ward : Not particularly, I mean there are examples in particle physics where one has a certain model, and based on that model, particles which have not been yet observed are predicted, and then the particle...

Melvyn Bragg : Can you give us some examples?

Martin Ward : Well the Higgs Boson , I mean I'm not a particle physicist, but there are many examples of this and then astronomer....particle physicists build huge accelerators to test these particular models. So there a number of examples and of course a good theory will make predictions that one has to go and test. A theory that makes no predictions is not a very good theory.

Melvyn Bragg : And so when did, as it were, the practicalities catch up with the theory in the study of black holes?

Martin Ward : Yes well how do we actually observe black holes? I mean I'm an observational astronomer, Martin's a theoretical astronomer, so he interprets our observations, and of course observations is what we have to have to move forward. It turns out that black holes can be detected observed, inferred by various types of observations and I won't give you a complete list because it's very long, but the interesting thing is what happens to matter. What do I mean by matter? I generally mean gas, that comes from somewhere else outside of the black hole, is pulled in by gravity - as Martin explains - towards the black hole just in the same way that the planets are orbiting around the sun, this gas is orbiting around the black hole, and gradually it's pulled in, it spirals in, and one of the ways we can actually observe them, we can infer them, is because this gas gets extremely hot, it becomes very dense because it's compressed, and it emits X-rays, and my particular discipline of X-ray astronomy is of course important in the detection of black holes, because that's what we use to actually see them. The hotter things get the higher energies they emit. It's the analogy with the furnace. If you have an ordinary furnace it glows red, if you wind up the temperature it gets to be yellow and then blue and then goes into the ultra-violet. The stuff that falls onto black holes gets even hotter - millions of degrees, and then we see it in X-rays, that has to be done from above the Earth's atmosphere.

Melvyn Bragg : So that actually took a development in technology to get that...

Martin Ward : Yes.

Melvyn Bragg : ...because Martin Reece earlier referred to the gravitational imprint - so we are - if we're going to be strict about the word "black" we cannot see them, and so we're inferring them from an adjacent....processes...

Martin Ward : Processes that occur near to the so-called event horizon. There are other ways to infer their existence and that is by their effect on other bodies, not by making them very hot, but just by disturbing the motions of stars for example, near to a black hole, such that we may have in the centre of our own galaxy, and by looking these stars as test particles, if you like, moving around the black hole, and that can be another way to infer the existence.

Melvyn Bragg : Martin Reece, what does a black hole do to spacetime in Einstein's General Theory of Relativity?

Martin Reece : Well the reason black holes are fascinating, is they exemplify the way in which Einstein's theory leads to surprising and counter intuitive conclusions in extreme situations. In our local context - on the Earth and in the solar system, gravity is fairly weak, and Newton's theory is effect good enough, but when gravity is very strong, or when motions are very fast, so things are moving about the speed of light, then we are not surprised that we have to go beyond Newton's theory.

This is why we can understand black holes better now than Mitchell was able to 200 years ago, we have a theory that can cope consistently with these extreme situations, and according to Einstein's theory, a black hole is an object where there's a definite sort of surface which is the place from which within no light can get out, and outside this surface we can calculate how gas or stars would move and that as Martin Ward explains is how we can infer the presence and properties of black holes. But what fascinates scientists and physicists in particular about black holes is that deep inside them, in the region that we can't directly observe, there lurks a very basic mystery indeed.

Melvyn Bragg : The singularity?

Martin Reece : The singularity - so-called, and the idea here is that deep inside the black hole, gravity becomes stronger and stronger and stronger and eventually according to the theory, it becomes infinite. Now what this in fact means is that the theory which Einstein gave us broke down and we have to have some new theory, and so deep inside black holes, there is a place where we know for sure we don't know enough physics to understand it. We need the kind of physics which unifies gravity - the force governing large-scale objects with quantum theory which governs small-scale objects. We need the same sort of breakthrough in physics which we will need also to understand the big bang at the beginning of the universe. So black holes point towards places we can actually observe in our universe, where physics transcends what we now understand.

Melvyn Bragg : And also black holes bring in this remarkable business of light bending, which Eddington in 1919, sort of proved empirically with the eclipse of the sun to justify, to validate Einstein's theory. But can you just talk about light bending Jocelyn Bell-Burnell and in terms of the event horizon around a black hole- I'm using a term....

Jocelyn Bell-Burnell : Right, yes.

Melvyn Bragg : ...that is..that I've got from you three, called the event horizon, and sometimes if light goes towards the black hole it disappears into the black hole, I mean we're talking fantasy as far as I am concerned, but here we go (laughter)...

Jocelyn Bell-Burnell : It's good fun!

Melvyn Bragg : ....and other times it bends around it, now can you tell us why sometimes light just disappears in this hole, and *cannot get out* - I think we must keep emphasising that - because once you're in this black hole....

Jocelyn Bell-Burnell : You've had it.

Melvyn Bragg : Not even light can get out-and light travels faster than anything we know, and that can't get out - so nothing can get out - so light disappears to this singularity that Martin says is beyond physics at the moment, but some light - seeing the black hole through the event.. on the horizon as it were, the event horizon - bends. Now it's over to you.

Jocelyn Bell-Burnell : Yeah. Right, I have a picture of a table top - not a very smooth table top - it's a billiard table but it's got dents in it, and as you shoot a ball across this table it gets deflected by the dents. A black hole is not just a dent, it's like a plug-hole in your billiard table, it goes right through to the darkness underneath. Instead of a billiard ball, we now have a ray of light, but it behaves the same way, and where the space is flat it trundles straight, but where there's a dimple in space it curves, just like your billiard ball curves, and where there's a black hole and it heads straight for it, it goes "whoops!" and down the hole.
Now if you keep a bit away from the plug-hole, where space is still curved but before it's gone really pluggish , hole-ish, then you can also get the light bent, but not falling in. If you aim light straight at a black hole it's going to go down, down the tube, but if you aim light a bit past the black hole, it'll just get bent, and what Eddington was doing in that eclipse expedition just after the 1st world war, was checking out a prediction of Einstein's that mass an gravity would bend light. He wasn't using a black hole, he was actually using the sun. He was using the sun at the time of an eclipse, so that the sunlight was blocked out, and you could actually see what was happening to rays of light, from beyond the sun, as they came past the sun, and so what Einstein was checking out was how much bend....

Martin Ward : Eddington.

Jocelyn Bell-Burnell : ...in a light ray as it goes round the edge of one of these dimples in our billiard table.

Melvyn Bragg : And can we just before we leave the...the anatomy of a black hole, Martin Ward, can you tell us about the event horizon, can you describe what that is and why it is so important?

Martin Ward : It's essentially an interface between what goes on inside the black hole and what goes on in the rest of the universe. The only way we can make progress in science is to make observations, experiments and so on, and the importance of the event horizon is that after something has passed through it, whatever that is - light, or gas or anything - after that its properties become very simple. It adds to the mass of the black hole, and therefore the event horizon gets a little bit bigger, but then it can't communicate, by any means - radio waves, any sort of communication is impossible after the event horizon, so we have to rely on the theory to know what happens to matter after it's gone through, so there's no more communication with the outside universe.

Melvyn Bragg : As I understand it, your team at Leicester was the first in the world to discover *physical* evidence of medium-sized black holes. Could you....is it possible for you to sum up the significance of that?

Martin Ward : Yes. Well, briefly, this of course was a big collaboration involving many astronomers throughout the world in the United States and Japan, because all these big instruments require a huge investment of money. We're part of this collaboration. We'll probably go on to discuss massive black holes and not so massive black holes. What we believe we may have discovered and the interesting thing about science is if you make an observation or discovery there's always several interpretations, so this is currently one of the interpretations.

We looked at a nearby galaxy, everything is relative terms isn't it? It's about 9 million light years away - this is in our "back yard" by our standards (low giggles), and we looked at it with an X-ray telescope and won't go into technical details, but it has tremendously fine resolution, acuity of vision, which we didn't have before for X-ray telescopes. The universe emits radiation across the electromagnetic spectrum, X-rays is one part, before we had a blurred view, and now we have a clear view. We looked at this particular galaxy and we saw a bright X-ray source, which was so bright that if we used the standard arguments that astronomers use to infer the mass of a black hole, one of them, then we believe that it has about 500 times the mass of the sun. So this is in between the 10....

Melvyn Bragg : Not the size - but the mass of the sun.

Martin Ward : ...the mass of the sun yes, so this is in between the small ones, diddly ones of a few times the mass of the sun, and the huge ones, in the centres of quasars, which are perhaps a billion times. Now what's the significance is that this particular source was not in the centre of the galaxy, and we would normally think that these massive black holes because of gravity, as Martin explained in the beginning would form at the very centre, because that's where the mass is. But this is many hundreds of light years away from the centre, so the question is, first of all is it an intermediate mass black hole? Another interpretation is possible. If it is, how on earth do you form these things not in the centre of the galaxy? It could be cannibalism actually, it could have been a passing galaxy which had a black hole in its centre, which had an accident- crashed into the other galaxy, and so we're just as a snapshot, seeing this little black hole by chance away from the nucleus.

Melvyn Bragg : You're just making it up, it's fun isn't it?! (laughter)

Martin Ward : It's one theory! But what's the significance, I think if it is an intermediate black hole then how do you form these things? If we could understand that and it's a nearby example, so we can study it in detail, maybe we've got clues to how to form the really massive ones.

Melvyn Bragg : Martin - Martin Reece, d'you want to come on on this and then I want to come to Jocelyn.

Martin Reece : Well I think what Martin Ward has just said emphasises that black holes are one of the zoo of objects that astronomers study, they study stars of all kinds, galaxies exploding stars, and they find evidence for different classes of black holes and we try and put these together into some grand evolutionary scenario for how the universe has evolved and formed these objects. But one thing that perhaps we should be clear about is the sizes of these black holes of different masses. The black holes that were first discovered and which are thought to be what happens in a star when it runs out of fuel and collapses - they would be a few miles across, whereas there *could* be black holes , indeed we think there *are* black holes at the centres of galaxies, which weigh as much as millions or even billions of stars, and they are proportionately bigger, the size of a black hole scales directly with its mass . So a black hole weighing a few million times as much as the sun, would be a few million times larger, and indeed would have quite a large volume inside it. So if you fell inside, you'd have quite a long time for leisured observation, before you got to this disastrous singularity.

Melvyn Bragg : Just to be absolutely clear about this difference of size/mass, so people ...if the sun were to turn into a black hole, the sun is X size, and the black hole would be considerably, considerably smaller?

Martin Reece : Yes the black hole...

Melvyn Bragg : How big is....? What's the diameter of the sun, and what would be the diameter of the black hole.

Martin Reece : The black hole that arose from the sun would be about 2-3 miles across.

Melvyn Bragg : Yes.

Jocelyn Bell-Burnell : The event horizon.

Martin Reece : A few times smaller than the neutron stars which Jocelyn Bell discovered. But a black hole of a kind that might exist in the centre of our galaxy, would weigh as much as about 3 million suns, and that would be about 10 million miles across, because the size goes with the mass. So there are these much bigger black holes, and there maybe the medium sized ones, which Martin Ward was talking about, but the theory of gravity doesn't have any sort of preferred size built into it, so in principle, according to Einstein's theory there could be black holes of any size and perhaps to pre-empt what we might come to later, there could also even theoretically be little tiny black holes the size of an atom, which would weigh as much as an asteroid or a mountain, could be squeezed down to the size of an atom to make a black hole. Those are theoretical constructs, that probably don't exist. But according to the theory there could be black holes of any size and any mass, and it's up to the astronomers to discover which of these actually exist in our universe and which were formed by different routes.

Melvyn Bragg : What they from or what they might do, but just to sort of keep mapping this out - Jocelyn you worked on, in fact Martin Reece said that you found these small black holes. What is.....what is ...what is the difference...? Are there any distinctions between the small black holes and those of intermediate size and supermassive size and...?

Jocelyn Bell-Burnell : Could we just clear up by what we mean by size? Because I think we're probably confusing the audience a bit.

Melvyn Bragg : Yeah.

Jocelyn Bell-Burnell : We've talked both about the mass of black holes and their physical size. The physical size of a black hole is perhaps the more confusing one, because one moment we're saying it collapses right down to the singularity, to point size. When we as professional astronomers talk about the size of the black hole, what we're usually talking about is the size of the *event horizon*, that mythical surface round the black hole which is it's Rubicon , and if you cross that event horizon, you are going down the black hole, come hell or high water. If you can keep outside the event horizon, you may escape, and for the sun that's about 3 miles across, and for the bigger things it's much, much bigger.
The physics of the star size, the intermediate mass, the supermassive black holes is all very similar, they are large, large gravitational masses with this so-called singularity at the centre and round them this event horizon. But interestingly, the effects that you would feel as you fell into these different kinds of black holes are different.
The star-sized black hole, as you cross the horizon there, you would feel the effects not just of gravity but of the gradient of gravity, tearing your body apart. Whereas if you were going into a supermassive black hole at the centre of a galaxy, you actually don't feel that effect, until much, much, much later, which in that case is *too* late.
But the basic physics very, very similar, yeah.

Melvyn Bragg : Can you ...can I come back to you for a moment Martin Reece, and then go to...? What role d'you think - you've talked about the - is there a supermassive black hole in our own galaxy? - What role...? D'you see it having....is there...are there words? I'm stumbling around for words.....are there words like role and function, are they relevant at all in this? Does it have a role, does it have a function?Does it have a place you can see which is interdependent on others, and helps others, is helped by others, the way we like to fit things in in engineering, and if we're lucky in the rest of life?

Martin Reece : Well they're certainly part of the picture, if you want to understand galaxies and stars, and the picture we have is that the universe started off as an expanding amorphous fireball after the big bang, and at some stage galaxies and stars condensed out, and they eventually evolved and around some of those stars we had planets etc etc. So we have this picture of cosmic evolution spread out over a bit more than 10, 000 million years, and at some stage black holes become part of this scenario, and they do indeed play two important roles.
One is that they are the end point of stars and so if we came back and looked at the universe in the far future, a lot

more of the stuff would have ended up in black holes, and these dead remnants, because gravity eventually will have won, and swallowed up a lot of material, so there's a general trend towards more and more of the material ending up in black holes, but they are also important to astronomers in trying to understand the universe, because they are able to manifest their presence in a very conspicuous way. Although a black hole doesn't put out any energy, something falling into a black hole, releases a tremendous amount of energy.

I mentioned that if something falls onto a neutron star, it releases a lot of energy in an explosion, and if something falls into a black hole, it releases far more energy per kilogram than you can get in any kind of explosion, even a nuclear explosion, and what this means is that black holes when they are not in empty space but surrounded by stars and gas that they are able to capture in the their (indistinct). They shine very brightly and indeed some of the most spectacular objects in the universe, that we observe, things called quasars, objects sending out jets, exploding stars of various kinds are energised by black holes, which are interacting with stuff close to them. So they are very important to us as astronomers, because they are conspicuous objects to study, and therefore allow us to probe distant parts of the universe, because they are the brightest things that we can see out there.

Melvyn Bragg : Martin Ward, Martin Reece referred to the big bang, 10, 000 million years ago or slightly more, and it has been suggested by Hawking that maybe black holes were there at the start of that and that they could be something to do with creating and seeding the galaxies. I think "seeding" is your word. Can we...can you just discuss that possibility?

Martin Ward : Well it's really, it's not my work of course, Martin Reece and his collaborators have written papers and others have as well. I think it's a sort of chicken and egg argument, and that is a fundamental question is "What's the dominant energy output process of the universe?" - one of the fundamental questions, and there are sort of two contenders really, one is star formation, in the same way that the Orion Nebula for example, is an example of stars forming in our own galaxy, it's called a stellar nursery sometimes, and these processes of course are nuclear processes, as Martin Reece has said, they're not terribly efficient in fact, in converting matter into energy by the $E=MC^2$. Black holes are more efficient - 10 times or even more than 10 times more efficient, and we don't actually know at the moment in the early stages of the universe, what the dominant energy process was. Whether it was accretion, that's the technical word, that means material falling onto the black hole - accreting onto the surface, no sorry - not the surface - through the event horizon - I should say and that produces a lot of energy or is it star formation? And it's a big open question, and the early generation of black holes, say ones that were formed perhaps just a billion years after the big bang, these are hypothetical, but they could have provided the seeds for galaxy formation - this work that Martin Reece has done, and one of the efforts in observational astronomy, particularly X-ray astronomy these days is to look for signatures of black hole activity in the early universe to try and quantify whether it was star forming regions or whether it was accretion that was producing a lot of the energy in the early stages.

Melvyn Bragg : Is there..if...are black holes always as it were, on the retreat? Because if they're always on the retreat, then the idea of them being a "seeding" wouldn't seem to me make any sense, but what I've heard so far is they get smaller and smaller, and more and more mass, pull more and more in, eventually reach a singularity which you've got zero....it's got infinite density, and zero size, and so are all black holes destined to disappear in that way and if so how can they be part of the expanding universe as it were?

Martin Ward : No I think there's a misconception here, I mean they don't disappear...

Melvyn Bragg : Well if you could clear it up I'd be very obliged!! (laughter)

Martin Ward : They can't get smaller - the event horizon can only be what it is now or larger if it accretes more material. As it accretes more material, the event horizon will scale up and become larger as I think Martin referred to earlier. So in the sense of them disappearing, perhaps the misconception is to do with whether we see evidence for them. It's believed that these very energetic things called quasars, that were formed in the early universe and emit tremendous amounts of energy, as much energy as the entire star output from our galaxy in a region the size of the solar system, but of course that only works, if they are feeding - another rather colloquial term - if material is falling onto them, if that dries up, if they stop feeding, then the black hole becomes really black, because it's only the effects of the matter falling onto the...through the event horizon, produces the energy. So it maybe that there are black holes sitting there which are not feeding, which we can't observe, so the era of black holes producing huge amounts of energy may be over, but they are still there, they haven't disappeared.

Melvyn Bragg : Jocelyn Bell-Burnell?

Jocelyn Bell-Burnell : An analogy due to a colleague of mine at the Open University . You see a child - a small child with chocolate all over it face, you rightly infer the child has been eating chocolate, you don't have direct evidence that the child has eaten the chocolate, but you do see the kind of side-effects?
It's a bit like that with material going into a black hole, you don't see the material that's gone in, but you see the effects that happen as the stuff goes in, the plastering round the mouth.

Melvyn Bragg : Martin Reece, this would lead me...on to the conclusion that if black holes are sucking everything in that comes anywhere near them, that eventually everything will be sucked into one black hole or other. That we're all destined...that the future of the universe that we all end up in a black hole?

Martin Reece : Yes things aren't quite as apocalyptic as that! (laughter) Black holes...

Melvyn Bragg : I'm just trying to encourage you!

Martin Reece : ...sure! Black holes are indeed growing, but we are for instance at an extremely safe distance from the one in the centre of our galaxy, there's no danger of that swallowing us up, so indeed, although they are growing, it would take a very long time before they swallowed up more than a tiny fraction of the galaxy. So....

Melvyn Bragg : But also - not to be apocalyptic - but to look far forward, I mean you speak...you people around this table speak very easily of sort of you know about 10 billion years ago...

Martin Reece : Right.

Melvyn Bragg : ...and that sort of thing, let's just take the odd billion or so years ahead. I mean are black holes...? They're not going to go away...are they going to go away? Are they going to grow? What's going to happen there?

Martin Reece : Well they are going to grow, but there is an interesting effect that will happen in the very, very far future, which does perhaps mean that they will not actually exist forever, and this is that there are tiny effects which are beyond what Einstein predicted in his theory, which allow for the microstructure of space, and the effect of **quantum theory**, and these will gradually erode away black holes, and this is an effect, which wasn't in Einstein's theory, but has been included later, and this will cause the so-called erosion or evaporation of black holes, but the time we're talking about over which this operates is far, far longer than the age of our present universe, and this I think indicates two things about the importance of black holes.

One is that although we understand black holes well enough to interpret some of the astronomical observations, there are still mysteries about the details, and also they do point towards new physics. New physics that may manifest itself deep inside black holes, and will manifest itself in present day black holes in the far future. So they are important because they are made as it were, from the fabric of space and time, and if you want to understand space and time, not only on the large scale of the universe, but on the tiny microscopic scale of atoms, we are going to have to have some new ideas to make sense of this, and black holes are going to be the kind of places where we can perhaps test these theories.

Melvyn Bragg : Briefly Jocelyn Bell-Burnell, is it possible to tell us what the effect on space and time is of the black holes? I mean if this studio went into a black hole, what would be the effect on our space and time?

Jocelyn Bell-Burnell : If this studio right now started falling into star-sized black hole, a star mass black hole, as opposed to one of the bigger ones. The first thing that would happen is that we'd begin to feel our bodies being pulled apart. Because not only was the gravity strong, but there's a very strong *gradient* of gravity, which means the gravity on the lower part of your body is much bigger than the gravity on the upper part of your body, and it's sufficiently strong that it would ultimately rip things apart in a most unpleasant manner.

Martin Reece : Spagettification, is the word for this.

Jocelyn Bell-Burnell : Spagettification, yes, you get long and thin, you go into sort of stranded...

Melvyn Bragg : A lot of people would pay for that!! (laughter)

Jocelyn Bell-Burnell : ....it's not a pleasant experience. If there was somebody else on another planet, able to observe us and the studio falling into the black hole, if they could watch the studio clock, which I'm sure is very precise, they would find it was running slow, and the closer we got into the black hole, the closer we got to the event horizon, the slower the clock would go. We wouldn't actually notice that effect, because our hearts and our whole metabolisms would be slowed in the same way, so actually what we'd just notice was the gravity.

But the mass of a black hole or indeed of any massive object, does alter clocks. One of the things that people in my speciality have to be aware of, where you are dealing with pulsars which are very accurate clocks - we have to be aware that our watches, our clocks, run at different rates between new moon and full moon. It's only about a millionth of a second difference, but it is there, and it's because at new moon, sun and moon are one on side of the Earth, at full moon, sun and moon are on opposite sides of the Earth, and so Earth experiences slightly different gravity in the two circumstances, and our clocks go at slightly different rates. But it's a much bigger effect near a black hole.

Melvyn Bragg : Yes. Martin Ward, is there any purchase at the present time - you're a consultant to the European Space Agency - and so they'll be looking for practical possibilities...

Martin Ward : Indeed.

Melvyn Bragg : ..is there any purchase on the idea that something...this terrible greed that we have that something should be done for US!! That something can come out of a black hole which would be, which we could harness?

Martin Ward : Yes well can we tax it! That sort of argument...(laughter) I frankly think no. I mean in principle, and I emphasise...in theory I should say we could possibly extract energy from a black hole because if you had two particles falling into a black hole, it would be possible that one could fall into the black hole and the other one could be -they call sling shot - shot out of the black hole with more energy, you could be extracting energy if you like from the black hole.

Melvyn Bragg : We could be digging energy out of the black holes.

Martin Ward : Well as I say, in theory, but I think the practicalities of this would be so difficult -I'd be interested to hear Martin's view - that this would really not be the way to go, I think we're really better off trying to solve how to do fusion effectively or something like that, but the European Space Agency of course isn't necessarily interested in making money out of space missions and so on, what they are interested in is making new observations and in the future there's a very interesting new satellite. ESA - the European Space Agency of course, is like NASA, slightly less money than NASA has.

But it does many things in space, and a European mission which maybe a joint one with NASA, is to look at the effect on the fabric of space of black holes as they merge together. We haven't talked about this, but we talked about material - gas - falling onto a black hole, but you can have a situation where two black holes are going around each other, and they can spiral in and they can merge into one black hole. And it turns out from the theory of General Relativity, when this happens, there is a pulse of gravity waves, so-called, which propagate out presumably at the speed of light, well that depends on whether they have any mass, and this can be detected by...Jocelyn gave an analogy - a nice analogy of the billiard table and the indentations which are caused by mass. So the experiment is to put a bit of graph paper - if you like on the billiard table in space, separate spacecraft separated by about 5 million kilometres, and to look for the wobbliness of the curvature of space as the gravity waves permeate through the universe towards us, and so we should be able to hear a chirp, sometimes it's referred to. It's like a ...there's an analogy with sound it has a certain frequency. So you can imagine it almost like an orchestra playing different notes, different chirps as different mass black holes merge together. This isn't fantasy, this is actually scientific theory.

Melvyn Bragg : Martin Reece you've talked about two black holes joining together, hurtling quietly through the universe, you didn't use "quietly" - I did - because it sounds ominous, but there....the ...d'you...can you discuss that in a second....but just to go back to the previous point, d'you think there's any...Roger Penrose has put up a hypothetical plan for using the powers of a black hole. Is there any potential in this at all?

Martin Reece : Well I think this is futuristic and almost science fiction, the idea of getting energy from them, and the other thing that, in principle, happens near a black hole is that if you go into the right orbit, but stay just outside the black hole, then the converse of what Jocelyn Bell was saying about the clock - if you fall in -is that if you are down there near the black hole, you see everything else in the external universe happening in a speeded up way, so if you go to a place near a black hole, you could in principle, see the external universe speeded up, and see its entire future, but that is science fiction of course, so returning to the more direct motivations for doing this sort of work, I should mention that the corrections to Newton's theory due to Einstein, are in fact significant enough to be used in a GPS satellite for getting our positions, that's one application, but the main reason why we study black holes is twofold I think.
First is they're clearly an important part of our cosmic habitat which is really part of our environment and secondly, gravity is a fundamental force of nature, and there's a limit to what we can do experimentally on Earth, and the cosmos provides us with a way in which we can study the laws of nature and the forces of nature under far more extreme conditions than we could ever simulate on Earth, and so if you want to understand forces such as electricity, nuclear forces and gravity, then we can learn a great deal from these observations and black holes in particular are objects that extremely strongly manifest the effects of gravity. So that's the motivation I would say.

Melvyn Bragg : Very, very briefly, Jocelyn Bell-Burnell, can I ask you one simple question are there...is there...are there...is there a possibility of white holes?

Jocelyn Bell-Burnell : Yes, the equations that predict black hole scan be run in the opposite direction of time, and in theory there could be white holes, places where material suddenly appears out of nowhere and spreads out into the universe.
But we've not seen any yet.

Melvyn Bragg : Well thank you very much, Jocelyn Bell-Burnell, Sir Martin Reece.

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