Black Holes And Baby Universes

This may be the first time, you have been addressed by a real computer. You may have seen science fiction films, like 2,000 and one, in which there were computers that spoke. But these films are really cheats: the computer parts were spoken by humans. The reason was, that computerized speech synthesizers were not sufficiently good, to be used in films or TV programs. But this speech synthesizer is a great improvement. It varies the intonation, and gives me a voice that sounds almost human, instead of like a Dalek. The only trouble is that it gives me an accent, that has been variously described, as American, Scandinavian, or Irish.

Now for my lecture. I will talk about black holes, which ain't as black as they are painted. Instead, I shall show that they can shine white hot. And they can be the proud parents of little baby universes.

There have been a number of science fiction stories, about space ships falling into black holes. A common suggestion is that, if the black hole is rotating, you can fall through a little hole in spacetime, and out into another region of the universe. This obviously raises great possibilities for space travel. Indeed, we need something like this, if travel to other stars, let alone other galaxies, is to be a practical proposition in the future. Otherwise, the fact that nothing can travel faster than light, means that the round trip to the nearest star, would

take at least 8 years. So much for a week-end break on Alpha Centauri! On the other hand, if one could pass through a black hole, one might reemerge anywhere in the universe. Quite how you choose your destination, is not clear: you might set out for a holiday in Virgo, and end up in the Crab Nebula.

I'm sorry to disappoint prospective galactic tourists, but this scenario doesn't work: if you jump into a black hole, you will get torn apart, and crushed out of existence. However, there is a sense in which the particles that make up your body, do carry on into another universe. I don't know if it would be much consolation to someone being made into spaghetti in a black hole, to know that his particles might survive.

Despite the slightly flippant tone I have adopted, this talk will be based on hard science. Most of what I shall say, is now agreed by other scientists working in this field, though this acceptance has come only fairly recently. The last part of the lecture, however, is based on very recent work, on which there is, as yet, no general consensus. But this work is arousing great interest and excitement.

Black holes were first thought about in Cambridge, England. A fellow of Queen's College, John Mitchell, wrote a paper about them in the Philosophical Transactions of the Royal Society, in 1783. His idea was this: suppose you fire a cannon ball vertically upwards from the surface of the earth. As it goes up, it will be slowed down by the effect of gravity. Eventually, it will stop going up, and will fall back to earth. However, if it had more than a certain critical speed, it would never stop and fall back, but would continue to move away. This critical speed is called, the escape velocity. It is about 7 miles a second for the earth, and about 390 miles a second for the Sun. Both of these velocities, are higher than the speed of a real cannon ball, but they are much smaller than the velocity of light, which is 186,000 miles a second. This means that gravity doesn't have much effect on light, and light can escape without difficulty from the earth or the Sun. However, Mitchell reasoned that it would be possible to have a star, that was sufficiently massive, and sufficiently small in size, that its escape velocity would be greater than the velocity of light. We would not be able to see such a star, because light from its surface would not reach us, but would be dragged back by its gravitational field. However, we might be able to detect the presence of the star, by the effect that its gravitational field would have on nearby matter.

It is not really consistent to treat light like cannon balls. According to an experiment carried out in 1887, light always travels at the same, constant, velocity. So it is difficult to see how gravity can cause light to fall back. This problem remained until 1915, when Einstein formulated the General Theory of Relativity. Even so, the implications of this theory for old stars, and other massive bodies, were not generally realized until the 1960s.

According to general relativity, space and time together can be regarded as forming a four dimensional space, called spacetime. This space is not flat, but it is distorted or curved, by the matter and energy in it. Objects try to move on straight lines through spacetime, but because it is curved, they move on paths, which are the nearest thing to a straight line in a curved space.

Similarly, light tries to move on a straight line, but because spacetime is curved, it appears to follow a path that is bent. We can actually observe this bending of light, during an eclipse. The Moon blocks out the Sun, and allows us to observe stars that are in almost the same direction as the Sun. We find that the stars appear to be in slightly different positions, because the light from them is bent by the curved spacetime near the Sun.

In the case of light passing near the Sun, the bending is

very small. However, if the Sun were to shrink until it was only a few miles across, the bending would be so great, that light leaving the Sun would not get away, but would be dragged back by the gravitational field. According to the theory of relativity, nothing can travel faster than light. So there would be a region from which it would be impossible for anything to escape. This region is called, a black hole. Its boundary is called, the event horizon. It is formed by the light, that just fails to get away from the black hole, but stays hovering on the edge.

It might sound ridiculous, to suggest that the Sun could shrink to being only a few miles across. One might think that matter could not be compressed that far. But it turns out, that it can.

The Sun is the size it is, because it is so hot. It is burning hydrogen into helium, like a controled H-bomb. The heat released in this process, generates a pressure, that enables the Sun to resist the attraction of its own gravity, which is trying to make it smaller.

Eventually, however, the Sun will run out of nuclear fuel. This will not happen for about another 5 billion years, so there's no great rush, to book your flight to another star. However, more massive stars will burn up their fuel much more rapidly. When they finish their fuel, they will start to lose heat, and to contract. If they are less than about twice the mass of the Sun, they will eventually stop contracting, and will settle down to a stable state. This state can be what is called, a white dwarf. These have radii of a few thousand miles, and densities of hundreds of tons per cubic inch. Or it can be a neutron star. These have a radius of about ten miles, and densities of billions of tons per cubic inch.

We observe large numbers of white dwarfs in our immediate neighbourhood in the galaxy. Neutron stars, however, were not observed until 1967, when Jocelyn Bell and Tony Hewish, at Cambridge, discovered objects called, Pulsars, which were emitting regular pulses of radio waves. At first, they wondered whether they had made contact with an alien civilization. Indeed, I remember that the seminar room, in which they announced their discovery, was decorated with figures of Little Green Men. In the end, however, they, and everyone else, came to the less romantic conclusion, that they were rotating neutron stars. This was bad news for writers of space westerns, but good news for the small number of us, who believed in black holes at that time. If stars could shrink as small as 10 or 20 miles across, to become neutron stars, one might expect that other stars could shrink even further, to become black holes.

A star with a mass more than about twice that of the Sun, can not settle down as a white dwarf, or neutron star. In some cases, the star may explode, and throw off matter, to bring its mass below the limit. But this won't happen in all cases. Some stars will shrink so small, that their gravitational fields will bend light so much, that it comes back towards the star. No further light, or anything else, will be able to escape. The stars will have become, black holes.

We now have fairly good observational evidence for a number of black holes. One of the best cases is Cygnus X 1. This is a system, consisting of a normal star, orbitting around an unseen companion. Matter seems to be being blown off the normal star, and falling on the companion. As it falls towards the companion, it develops a spiral motion, like water running out of a bath. It will get very hot, and will give off the x-rays that are observed. The unseen companion must be very small, a white dwarf, neutron star, or black hole. However, one can show that the mass of the companion must be at least six times that of the Sun. This is too much for it to be a white dwarf, or a neutron star. So, it has to be a black hole.

I once bet Kip Thorne, of the California Institute of

Technology, that Cygnus X 1 does not contain a black hole. This was not because I didn't believe that there really was a black hole in Cygnus X 1. Rather, it was an insurance policy. I had done a lot of work on black holes, and it all would have been wasted, if it had turned out that black holes didn't exist. But then, at least, I would have had the consolation of winning my bet. However, I now consider the evidence for black holes so compelling, that I have conceded the bet. I have given Kip Thorne a subscription to Penthouse.

At first, space travel through black holes, seemed quite possible. There are solutions of Einstein's General Theory of Relativity, in which it is possible to fall into a black hole, and come out in another region of the universe. However, later work showed that these solutions were all very unstable: the slightest disturbance, such as the presence of a spaceship, would destroy the wormhole, or passage, leading from the black hole, to elsewhere in the universe. The spaceship would be torn apart by infinitely strong forces.

After that, it seemed hopeless. Black holes might be useful for getting rid of garbage, or even some of one's friends. But they were "a country from which no traveller returns". However, everything I have been saying so far, has been based on calculations using Einstein's General Theory of Relativity. This theory is in excellent agreement with all the observations we have made. But we know it can not be quite right, because it doesn't incorporate the Uncertainty Principle of Quantum Mechanics. The Uncertainty Principle says, that particles can not have both a well defined position, and a well defined velocity. The more precisely you measure the position of a particle, the less precisely you can measure its velocity, and vice versa.

In 1973, I started investigating what difference the Uncertainty Principle would make to black holes. To my great surprise, and that of everyone else, I found that it meant that black holes are not completely black. They would be sending out radiation and particles, at a steady rate. My results were received with general disbelief, when I announced them at a conference near Oxford. The chairman of the session, said they were nonsense, and wrote a paper saying so. However, when other people repeated my calculations, they found the same effect. So, in the end, even the chairman agreed I was right.

How can radiation escape from the gravitational field of a black hole. The answer is, the Uncertainty Principle, allows particles to travel faster than light, for a small distance: if a particle is confined to a certain region, like a black hole, there has to be a bit of uncertainty in its speed. So it is possible for the speed of the particle, to be greater than the speed of light. This would enable the particle, to get out through the event horizon, and escape from the black hole. The smaller the black hole, the greater will be the uncertainty in the speed of the particle. Thus particles and radiation, will leak more rapidly out of a small black hole, than out of a large black hole. For a black hole of the mass of the Sun, the rate of emission is so low, it can not be measured. But there may be much smaller black holes, which may have been formed in the very early universe. If there were enough of these very small black holes, we could detect the radiation they gave out. People have looked for radiation from little black holes, but have not found it so far. It seems there are not many little black holes in the universe, which is a pity.

As a black hole gives off particles and radiation, it will lose mass. This will cause the black hole to get smaller, and to send out particles more rapidly. Eventually, it will get down to zero mass, and will disappear completely. The particles and radiation that come out of a black hole, are in general different from those that fell into the hole.

One can therefore ask: what happened to the original particles, that collapsed to form the black hole. And what happened to any astronauts, or spaceships, that fell into the black hole later on. It seems the answer is, that they go off into a little baby universe of their own. A small, self-contained universe branches off from our region of the universe. This baby universe may join on again to our region of spacetime. If it does, it would appear to us to be another black hole, which formed, and then evaporated. Particles that fell into one black hole, would appear as particles emitted by the other black hole, and vice versa.

This sounds just what is required to allow space travel through black holes. You just steer your space ship into a suitable black hole. It better be a pretty big one, or the gravitational forces will tear you into spaghetti, before you get inside. You would then hope to reappear out of some other hole, though you wouldn't be able to choose, where.

However, there's a snag in this intergalactic transportation scheme. The baby universes, that take the particles that fell into the hole, occur in what is called, imaginary time. Imaginary time may sound like science fiction, but it is a well defined mathematical concept. It is time measured using what are called imaginary numbers. The use of imaginary time seems essential, in order to formulate Quantum Mechanics, and the Uncertainty Principle properly. It can be thought of as a direction of time, that is at right angles to the ordinary, or "real" time that we experience.

In real time, an astronaut who fell into a black hole, would come to a sticky end. He would be torn apart, by the difference between the gravitational force on his head and his feet. Even the particles that made up his body, would not survive. Their histories, in real time, would come to an end, at a singularity. However, the histories of the particles, in imaginary time, would continue. They

まとめますと、空間の狭い領域に多量の物質が集中するとブラックホールがつくられます。物体はブラックホールに落ちることはできますが、そこから出るには、光より速い速度が必要です。これは通常、大きい物体には不可能なことですが、量子力学の不確定性原理では、個々の粒子はある短い距離だけなら光より速く動くことを可能としています。これによって、粒子と放射がブラックホールからゆっくりと漏れ出すことができるのです。ブラックホールは収縮し、ついには完全に消え去ります。ブラックホールに落ちた粒子は小さなベビーユニバースに行き、そして他のブラックホールから出てきます。しかし、このことは長距離の宇宙旅行には何の役にも立たないでしょう。

would pass into the baby universe, and would reemerge as the particles emitted by another black hole. Thus, in a sense, the astronaut would be transported to another region of the universe. However, the particles that emerged, would not look much like the astronaut. Nor, might it be much consolation to him, as he ran into the singularity in real time, to know that his particles will survive in imaginary time. The motto for anyone who falls into a black hole must be: Think Imaginary.

What all this means, is that going through a black hole, is unlikely to prove a popular and reliable method of space travel. First of all, you would have to get there by travelling in imaginary time, and not care that your history in real time came to a sticky end. Second, you couldn't really choose your destination. It would be a bit like travelling on some airlines I could name.

To sum up. A sufficient concentration of matter in a small region of space, will create a black hole. Objects can fall into a black hole, but to get out, would require a speed greater than the speed of light. This is not normally possible for large objects, but the Uncertainty Principle of Quantum Mechanics, allows individual particles to travel faster than that, for a short distance. This allows particles and radiation to leak slowly out of a black hole. The hole will shrink, and eventually disappear completely. The particles that fell into the black hole, will go off into a little baby universe, and will come out of another black hole. However, this will not be any use for long distance space travel.

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