Black holes

At the 2015 Hay-on-Wye Science and Music Festival 'How the Light Gets in', in May this year, I took part in a debate about the existence of black holes, under the title 'Bang Goes Another Theory of the Universe'. The other two participants were Prof Laura Mersini-Houghton of the University of North Carolina, Prof Pedro Ferreira of the University of Oxford.

Prof Mersinin-Houghton had recently argued that black holes can not form because the Hawking radiation they emit would stop the infall. Pedro talked about the immense successes of General Relativity and I was there to talk about the astrophysical evidence for black holes.

What's interesting about black holes is the interaction between experiment and observations on the one hand, and the mathematical models we invent to explain them, on the other.

Einstein's 1916 General Theory of Relativity immediately solved a century-old problem with the orbit of Mercury and predicted something new, the bending of light round the Sun, which was confirmed by observations during the 1919 eclipse of the Sun. But from these very first solutions of Einstein's equations it seemed that something funny happened at a particular distance from a point-mass M, at distance $2GM/c^2$. At first this seemed an academic point, because this distance is only 3 km for the mass of the Sun, compared with its radius of 1 million kilometers.

Then in 1939 Oppenheimer and Sneider showed that for a star above a certain mass, which we now know to be about 20 times the mass of the Sun, the end point of its evolution, after it has exhausted its nuclear fuel, is collapse to a point, a singularity, and that this would be hidden from view inside the 'event horizon'. As their 1939 abstract says:

> 'The total time of collapse for an observer comoving with the stellar matter is finite, and for this idealized case and typical stellar masses, of the order of a day; an external observer sees the star asymptotically shrinking to its gravitational radius.'

In 1964 the first of these collapsed massive stars was found, the X-ray source Cygnus X-1. The idea is that we have a close pair of massive stars. One (>20Msun) reaches the end of its life, explodes as a supernova and forms a black hole. The companion star also evolves and grows to be a red giant star. Matter flows out from this companion and falls towards the black hole. As it falls inwards it swirls around it to form an accretion disc. At the inner edge, near the event horizon of the black hole, the gas in the disc becomes very hot and radiates X-rays. So we see an X-ray binary system in which only one star is visible, orbiting an unseen, X-ray emitting object. Dozens of other stellar mass black holes have subsequently been found.

In the same year, at the First Texas Symposium on relativistic astrophysics, for which the main topic was the nature of the newly discovered quasi-stellar radio sources, Hoyle and Fowler proposed the existence of supermassive collapsed objects, of mass one hundred million times the mass of the Sun, whose fate was likely to be a black hole.

In 1965 Roger Penrose investigated trapped surfaces around a collapsing object and showed that a singularity really would develop. His work was extended by Stephen Hawking, Brandon Carter, David Robinson, Jacob Beckenstein and others. From this work came the 'No hair postulate': a black hole has only mass, angular momentum, and charge. In 1967 Wheeler coined the term 'black hole'

In 1974, in his most important work, Hawking discovered that black holes can radiate. Hawking's idea was that a particle-antiparticle pair form spontaneously just outside the event horizon, one falls in and the other escapes. The black hole appears to radiate the escaping particle. The 'no hair' theorem' means that information about the infalling particle is lost. There has been controversy for 40 years about this and the current consensus is that information is probably not lost.

The matter collapsing to form the black hole, and any subsequent matter falling in, remains, as far as an external observer is concerned (and this is true even if we are orbiting quite close to the black hole), suspended just outside the event horizon of the black hole. In a sense it does not matter, as far as astrophysical processes are concerned, whether the black hole really forms or not, whether there really is a singularity inside the event horizon, because the external gravitational effects are the same. The information about the infalling particle remains plastered against the event horizon for ever as far as the external observer is concerned.

In 1995 X-ray iron lines from supermassive black holes showed the effects of a gravitational redshift, confirming that the X-ray emission is arising in the strong gravitational field of a black hole, and in 1996 iron line profiles showed that some supermassive black holes are rotating (an idea put forward by Roy Kerr in 1963)

Two groups led by Reinhard Genzel (Munich) and Andrea Gehz (Caltech) have mapped orbits of stars around the black hole at the centre of the Milky Way (Sgr A). There is a great U-tube video of these stars orbiting the centre of our Galaxy.

So there are three interesting aspects of black holes:

(1) theory predicted black holes and then astronomers found them
(2) theory predicts a singularity at the centre, where General Relativity breaks down and we need a new theory
(3) this singularity is hidden from view and from the point of view of the external observer, they never see the collapsing matter cross the horizon.

So black holes really do exist but they are weird. What doesn't really exist is Hawking radiation. For the stellar mass black holes, the time for this radiation to evaporate the black hole is 10^{70} years, essentially infinite. In fact over the whole history of the universe just one high energy photon or particle would be emitted. So whether black holes are evaporating, as predicted by Hawking, or blowing up, as predicted controversially by Laura Mersinin-Houghton, it is happening so slowly that even when all stars have died and life in the universe is over, it won't even have got started.

Of course theorists hope there might be microscopically small black holes which we can watch evaporate away in real time. Perhaps these will be seen by the Large Hadron Collider. But current astrophysics and cosmology do not need them.

Does modern theoretical physics have a problem ? Perhaps the problem is too much focus on mathematical exotica like Hawking radiation (unobservable) and string theory (makes no predictions).

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