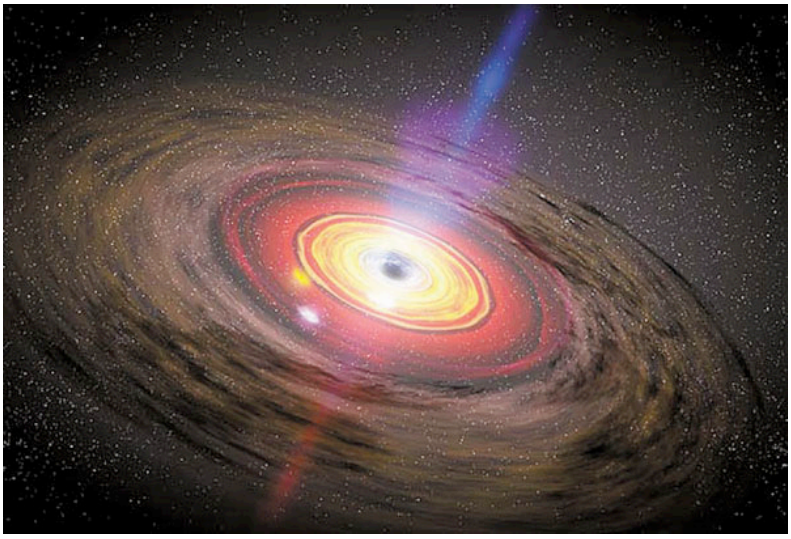
Black Holes



Loosely speaking, a black hole is a region of space that has so much mass concentrated in it that there is no way for a nearby object to escape its gravitational pull. Since our best theory of gravity at the moment is Einstein's general theory of relativity, we have to delve into some results of this theory to understand black holes in detail, but let's start off slowly, by thinking about gravity under fairly simple circumstances.

Suppose that you are standing on the surface of a planet. You throw a rock straight up into the air. Assuming you don't throw it too hard, it will rise for a while, but eventually the acceleration due to the planet's gravity will make it start to fall down again. If you threw the rock hard enough, though, you could make it escape the planet's gravity entirely. It would keep on rising forever. The speed with which you need to throw the rock in order that it just barely escapes the planet's gravity is called the "escape velocity." As you would expect, the escape velocity depends on the mass of the planet: if the planet is extremely massive, then its gravity is very strong, and the escape velocity is high. A lighter planet would have a smaller escape velocity. The escape velocity also depends on how far you are from the planet's centre: the closer you are, the higher the escape velocity. The Earth's escape velocity is 11.2 kilometres per second (about 25,000 m.p.h.), while the Moon's is only 2.4 kilometres per second (about 5300 m.p.h.).

Now imagine an object with such an enormous concentration of mass in such a small radius that its escape velocity was greater than the velocity of light. Then, since nothing can go faster than light, nothing can escape the object's gravitational field. Even a beam of light would be pulled back by gravity and would be unable to escape.

The idea of a mass concentration so dense that even light would be trapped goes all the way back to Laplace in the 18th century. Almost immediately after Einstein developed general relativity, Karl Schwarzschild discovered a mathematical solution to the equations of the theory that described such an object. It was only much later, with the work of such people as Oppenheimer, Volkoff, and Snyder in the 1930's, that people thought seriously about the possibility that such objects might actually exist in the Universe. (Yes, this is the same Oppenheimer who ran the Manhattan Project.) These researchers showed that when a sufficiently massive star runs out of fuel, it is unable to support itself against its own gravitational pull, and it should collapse into a black hole.

In general relativity, gravity is a manifestation of the curvature of spacetime. Massive objects distort space and time, so that the usual rules of geometry don't apply anymore. Near a black hole, this distortion of space is extremely severe and causes black holes to have some very strange properties. In particular, a black hole has something called an 'event horizon.' This is a spherical surface that marks the boundary of the black hole. You can pass in through the horizon, but you can't get back out. In fact, once you've crossed the horizon, you're doomed to move inexorably closer and closer to the 'singularity' at the centre of the black hole.

You can think of the horizon as the place where the escape velocity equals the velocity of light. Outside of the horizon, the escape velocity is less than the speed of light, so if you fire your rockets hard enough, you can give yourself enough energy to get away. But if you find yourself inside the horizon, then no matter how powerful your rockets are, you can't escape.

The horizon has some very strange geometrical properties. To an observer who is sitting still somewhere far away from the black hole, the horizon seems to be a nice, static, unmoving spherical surface. But once you get close to the horizon, you realize that it has a very large velocity. In fact, it is moving outward at the speed of light! That explains why it is easy to cross the horizon in the inward direction, but impossible to get back out. Since the horizon is moving out at the speed of light, in order to escape back across it, you would have to travel faster than light. You can't go faster than light, and so you can't escape from the black hole.

(If all of this sounds very strange, don't worry. It is strange. The horizon is in a certain sense sitting still, but in another sense it is flying out at the speed of light. It's a bit like Alice in "Through the Looking-Glass": she has to run as fast as she can just to stay in one place.)

Once you're inside of the horizon, spacetime is distorted so much that the coordinates describing radial distance and time switch roles. That is, "r", the coordinate that describes how far away you are from the centre, is a timelike coordinate, and "t" is a spacelike one. One consequence of this is that you can't stop yourself from moving to smaller and smaller values of r, just as under ordinary circumstances you can't avoid moving towards the future (that is, towards larger and larger values of t). Eventually, you're bound to hit the singularity at $r = 0$. You might try to avoid it by firing your rockets, but it's futile: no matter which direction you run, you can't avoid your future. Trying to avoid the centre of a black hole once you've crossed the horizon is just like trying to avoid next Thursday.

Incidentally, the name 'black hole' was invented by John Archibald Wheeler, and seems to have stuck because it was much catchier than previous names. Before Wheeler came along, these objects were often referred to as 'frozen stars.'

Fictional Image: http://www.gilroydispatch.com/content/img/f150509/black-hole-0322.jpg

What is a black hole?: http://cosmology.berkeley.edu/Education/BHfaq.html