Hawking radiation

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In physics, **Hawking radiation** is thermal radiation thought to be emitted by black holes due to quantum effects. It is named after British physicist Stephen Hawking who worked out the theoretical argument for its existence in 1974. Hawking's discovery became the first convincing insight into quantum gravity. However, the existence of Hawking radiation remains controversial. .

Overview

Black holes are sites of immense gravitational attraction into which surrounding matter is drawn by gravitational forces. Classically, the gravitation is so powerful that nothing, not even radiation or light (hence why it is black as no light is reflecting from it), can escape from the black hole. However, by doing a calculation in the framework of quantum field theory in curved spacetimes, Hawking showed that quantum effects allow black holes to emit radiations in a thermal spectrum.

Physical insight on the process may be gained by imagining that particle antiparticle radiation is emitted from just beyond the event horizon. This radiation does not come directly from the black hole itself, but rather is a result of virtual particles being "boosted" by the black hole's gravitation into becoming real particles.

A more precise, but still much simplified view of the process is that vacuum fluctuations cause a particle-antiparticle pair to appear close to the event horizon of a black hole. One of the pair falls into the black hole whilst the other escapes. In order to fill the energy 'hole' left by the pair's spontaneous creation, energy tunnels out of the black hole and across the event horizon. By this process the black hole loses mass, and to an outside observer it would appear that the black hole has just emitted a particle.

An example

A black hole of one solar mass has a temperature of only 60 nanokelvins; in fact, such a black hole would absorb far more cosmic microwave background radiation than it emits. A black hole of 4.5×10^{22} kg (about the mass of the Moon) would be in equilibrium at 2.7 kelvins, absorbing as much radiation as it emits. Yet smaller primordial black holes would emit more than they absorb, and thereby lose mass.

Problems with the theory

The trans-Planckian problem may raise doubts on the physical validity of Hawking's result. Hawking's original derivation employed field modes of arbitrarily high frequency near the black hole horizon, although these do not appear in the final result. In particular, he used modes of frequency higher than the inverse Planck time, and at these scales the physical laws are unknown. A number of alternative approaches to the Hawking radiation have appeared in order to try to overcome or address this problem. Some of these are in connection with the Unruh effect.

The Hawking Radiation shows that the laws of black hole thermodynamics have a complete physical meaning.

Emission process

A black hole emits thermal radiation at a temperature

$$T_H = \frac{\kappa}{2\pi},$$

in natural units with G, c, $\hbar$ and k equal to 1, and where κ is the surface gravity of the horizon.

In particular, the radiation from a Schwarzschild black hole is black-body radiation with temperature:

$$T = \frac{\hbar\, c^3}{8\pi G M k}$$

where $\hbar$ is the reduced Planck constant, c is the speed of light, k is the Boltzmann constant, G is the gravitational constant, and M is the mass of the black hole.

Black hole evaporation

When particles escape, the black hole loses a small amount of its energy and therefore of its mass (recall that mass and energy are related by Einstein's famous equation $E = mc^2$).

The power emitted by a black hole in the form of Hawking radiation can easily be estimated for the simplest case of a nonrotating, non-charged Schwarzschild black hole of mass M. Combining the formulae for the Schwarzschild radius of the black hole, the Stefan-Boltzmann law of black-body radiation, the above formula for the temperature of the radiation, and the formula for the surface area of a sphere (the black hole's event horizon) we get:

$$P = \frac{\hbar\, c^6}{15360\, \pi\, G^2 M^2}$$

where P is the energy outflow, $\hbar$ is the reduced Planck constant, c is the speed of light, and G is the gravitational constant. It is worth mentioning that the above formula has not yet been derived in the framework of semiclassical gravity.

The power in the Hawking radiation from a solar mass black hole turns out to be a minuscule 10^{-28} watts. It is indeed an extremely good approximation to call such an object 'black'.

Under the assumption of an otherwise empty universe, so that no matter or cosmic microwave background radiation falls into the black hole, it is possible to calculate how long it would take for the black hole to evaporate. The black hole's mass is now a function $M(t)$ of time t. The time that the black hole takes to evaporate is:

$$t_{\mathrm{ev}} = \frac{5120\, \pi\, G^2 M_0^3}{\hbar\, c^4}$$

For a black hole of one solar mass (about 2×10^{30} kg), we get an evaporation time of 10^{67} years—much longer than the current age of the universe. But for a black hole of 10^{11} kg, the evaporation time is about 3 billion years. This is why some astronomers are searching for signs of exploding primordial black holes.

In common units,

$$P = 3.563\,45 \times 10^{32} \left[\frac{\mathrm{kg}}{M}\right]^2 \mathrm{W}$$

$$t_{\mathrm{ev}} = 8.407\,16 \times 10^{-17} \left[\frac{M_0}{\mathrm{kg}}\right]^3 \mathrm{s} \;\;\approx\;\; 2.66 \times 10^{-24} \left[\frac{M_0}{\mathrm{kg}}\right]^3 \mathrm{yr}$$

$$M_0 = 2.282\,71 \times 10^{5} \left[\frac{t_{\mathrm{ev}}}{\mathrm{s}}\right]^{1/3} \mathrm{kg} \;\;\approx\;\; 7.2 \times 10^{7} \left[\frac{t_{\mathrm{ev}}}{\mathrm{yr}}\right]^{1/3} \mathrm{kg}$$

So, for instance, a 1 second-lived black hole has a mass of 2.28×10^5 kg, equivalent to an energy of 2.05×10^{22} J that could be released by 5×10^6 megatons of TNT. The initial power is 6.84×10^{21} W.

Black hole evaporation has several significant consequences:

- Black hole evaporation produces a more consistent view of black hole thermodynamics, by showing how black holes interact thermally with the rest of the universe.
- Unlike most objects, a black hole's temperature increases as it radiates away mass. The rate of temperature increase is exponential, with the most likely endpoint being the dissolution of the black hole in a violent burst of gamma rays. A complete description of this dissolution requires a model of quantum gravity however, as it occurs when the black hole approaches Planck mass and Planck radius.
- The simplest models of black hole evaporation lead to the black hole information paradox. The information content of a black hole appears to be lost when it evaporates, as under these models the Hawking radiation is random (containing no information). A number of solutions to this problem have been proposed, including suggestions that Hawking radiation is perturbed to contain the missing information, that the Hawking evaporation leaves some form of remnant particle containing the missing information, and that information is allowed to be lost under these conditions.